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THE PROBLEM OF THE ANORTHOSITES

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STATEMENT OF THE PROBLEM

Seldom can it be truly said that the puzzling feature of any object is its simplicity, yet of all the problems that the anorthosites present to us for solution the most difficult is their simple mineralogical composition. Bunsen long ago taught geologists to think of rock magmas as solutions, and the so-called solution theory[1] of magmas has now gained general acceptance. We have been enabled to understand many features of magmas that without the aid of the theory of solutions would remain incomprehensible. We understand why the order of separation of mineral from a magma is not simply the order of their fusibility. We understand also why a rock magma remains liquid at temperatures far below the temperatures of fusion of the individual minerals that enter into the magma and, therefore, why magmatic temperatures are comparatively moderate. It is because the individual minerals exist in the magma in mutual solution and therefore have their specific properties modified. But when we turn to anorthosites we find

[1] Nowadays it is scarcely proper to speak of the solution theory of magmas, for magmas are solution in virtue of the definition of a solution rather than by theory. On the other hand, to speak of the theory of solutions as applied to magmas is, of course, entirely permissible.

them made up almost exclusively of the single mineral, plagioclase. What, then, of the magmatic temperatures of anorthosites? Have we in them an exception to the rule of moderate magmatic temperatures?

Anorthosites apparently exert no exceptional influence upon surrounding rocks. Foreign inclusions, even very susceptible ones, are apparently not melted up. Inclusions of quartz-bearing rocks do not have their quartz changed to tridymite or cristobalite. Nothing in the field evidence gives us any reason to believe that anorthosites are in any way exceptional in this respect. Neither do we find any comfort in field evidence if we entertain the possibility that, in the absence of other minerals in amounts adequate to produce a great lowering of the melting temperature of plagioclase, there was present instead a sufficient amount of the much more potent "mineralizers." Typical anorthosite is notably free from all those minerals which, when present in rocks, constitute the principal evidence of the presence of volatile components in significant amounts in their magmas.[1]

An alternative possibility is that the material of anorthosites actually was in solution in something else at one time and that it differentiated from this solution. This alternative is more in harmony with general opinion, for few would state that beneath those places where we find anorthosites, there existed some anorthosite magma and that it simply was always there. It is generally believed, rather, that anorthosites are differentiates of gabbroid magma, the belief being based on field association. But it is also commonly believed that the differentiation took place in some manner in the liquid state and produced anorthosite magma. Now we must realize, and face the fact squarely, that anorthosite magma, however produced, is, nevertheless, anorthosite magma, and must exhibit the appropriate characteristics. It could separate as a liquid, by any process whatsoever, only at temperatures at which it could exist as a liquid, and we are immediately presented with precisely the same temperature problem. Anorthosites, as we have seen, do not give evidence of ever being at a temperature approaching that requisite to melt plagioclase.

[1] This matter is considered in greater detail in connection with the Morin anorthosite.

THE PROPOSED SOLUTION

For this reason in part, but also because careful consideration of all the possibilities and much experimental work to test these possibilities seem to indicate the inadequacy of any process other than crystallization, it is believed that the gabbroid magma must proceed to crystallization, and that anorthosite masses are simply collected plagioclase crystals. It is believed, then, that anorthosites were never liquid as such, but that their material when liquid was part of a solution probably of a gabbroid nature. Only in virtue of the sorting of solid, crystalline units from this solution does anorthosite come into being.

Having arrived at this belief, we may examine the anorthosites to see in how far they agree with its consequences, but before this can be done it is necessary to discuss in detail the process of sorting of crystals.

THE PROCESS OF ACCUMULATION OF CRYSTALS

General relations involved.—It must be admitted that the problem of the method of accumulation of plagioclase crystals for the formation of a mass of anorthosite is not a simple one. If the plagioclase crystals were much heavier or much lighter than gabbroic magma, all would be plain sailing. It could then be assumed that the crystals sank in the magma or floated in it, and were therefore accumulated at the bottom or at the top. But laboratory determinations of the densities of calcic plagioclase crystals and of molten gabbro place them very close together, with the crystals a very little lighter, and while the difference would not be the same and might even be in the opposite direction, there is, nevertheless, every reason to believe that it would still be small under natural conditions. As a matter of fact, we actually find this similarity of density expressed in the composition of anorthosites. If plagioclase were much lighter or much heavier, the mere accumulation of crystals would be, as we have seen, a simple matter, but the anorthosite masses formed would not be such as we find them, a fact which will become obvious from the following considerations.

During the crystallization of a magma involving the precipitation of mix-crystals the crystals first deposited are rich in the higher-

melting component of the mix-crystal series. As the magma cools, especially if it cools very slowly, these crystals continually change in composition as a result of interchange of material between liquid and crystals, the change being always in the direction of enrichment in the lower-melting component. But this change is fully accomplished only when adequate liquid is available. If the crystals are heavy and accumulate toward the bottom, the small amount of liquid there available cannot continue indefinitely to enrich the crystals in the lower-melting component. They therefore remain very rich in the higher-melting component, increasingly so the greater the preliminary accumulation of crystals. Vogt's important statistical study of the anchi-monomineralic rocks shows quite definitely that in the case of peridotites the ratio of Mg_2SiO_4 to Fe_2SiO_4 in the olivine increases directly with the proportion of olivine in the rock.[1] The orthorhombic pyroxenes apparently follow a parallel law.

This is, then, precisely as deduced above for rocks formed by the accumulation of heavy early crystals. If plagioclase were a very heavy or a very light mineral, we should find a similar relation to hold for it, namely, the greater the proportion of plagioclase in a rock, the greater would be the proportion of anorthite in the plagioclase. But when we turn to Vogt's similar study of anorthosites, we find in them a quite different tendency. The richer a rock is in plagioclase, the greater the tendency for the plagioclase to be, not a very calcic one, but the intermediate one, labradorite.[2] This character of the plagioclase is, it is believed, directly connected with the fact that the plagioclase being precipitated from gabbroic magma sensibly matches the magma in density. It is perhaps slightly lighter than the magma, but usually not sufficiently so to cause it to accumulate locally and to form masses of crystals much enriched in the higher-melting component as do olivine and pyroxene. Instead, it remains practically suspended in the liquid, with probably a very slight tendency to rise at first, and the whole of the liquid is available for the production of the change of com-

[1] J. H. L. Vogt, "Über anchi-monomineralische und anchi-eutektische Eruptivgesteine," *Vid. Selsk. Skr.* I, No. 10 (1908), pp. 24–25.

[2] Vogt, *op. cit.*, p. 41.

position that ensues as the temperature falls. Thus, though the earlier crystals of plagioclase are basic bytownite, they are, in nearly all cases, gradually made over into labradorite by the liquid in which they remain suspended. In the meantime the liquid has suffered impoverishment in ferromagnesian constituents and eventually becomes decisively lighter than the plagioclase crystals. Then and then only, as a rule, does subsidence of plagioclase crystals become an important factor, and masses of anorthosite, anorthosite-gabbro, etc., are formed according to the degree of concentration of crystals. It is to be noted that this lighter liquid from which the labradorite crystals accumulate is now, of course, no longer gabbroic, but, as a result of removal of femic constituents and plagioclase, it approaches syenitic composition, and with continuation of the process actually attains the composition of syenite or granite. In the ideal case in which the process had free scope the resultant mass would be stratified, and would consist of syenite-granite, anorthosite, and pyroxenite in descending order with, in some cases, peridotites at the base. Of all these the only type that was ever liquid as such would be the syenite-granite, though liquids of every composition intermediate between that of the original gabbro and the syenite would be concerned in the process and might occur as chilled borders or in satellitic bodies. The anorthosites should be intimately related to gabbro, therefore, but as intimately related to syenite also, which might occur as interstitial material of late crystallization in some of the phases. By increase of this interstitial material gradual transition into syenite might occur.

Intimate field association of anorthosite with gabbro and with syenite is a fact that no one will question. Some have emphasized its relation to gabbro and some that to syenite, but the emphasis is due as much to the personal element and to the kind of exposures in any particular area as to any fundamental difference between the anorthosites of one area and of another. One would expect, to be sure, that the andesine-labradorite phase of an anorthosite mass would be the more intimately related to syenite, and the labradorite-bytownite phase to gabbro.

Quantitative considerations.—We can perhaps form a better idea of the quantitative relations involved in the process of collection of

crystals if we examine the crystallization of mixtures of the system —diopside, anorthite, albite—not because proportions will be the same, but because they will be rather of the same order in the natural system and will aid us in deciding whether the process is a reasonable method of producing anorthosites as we find them.

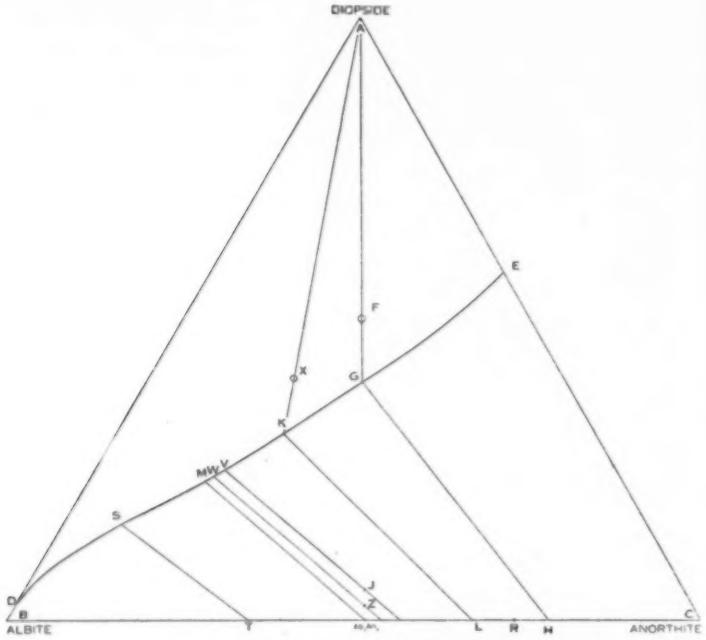

FIG. 1.—Diagram of crystallization in plagioclase-diopside melts

A liquid of composition *F* (Fig. 1), which contains 50 per cent diopside and 50 per cent labradorite (Ab_1An_1), begins to crystallize at 1275°, diopside separating first. As the temperature falls the composition of the liquid changes from *F* along *AFG* (directly away from diopside), and when the temperature 1235° is reached the mass consists of 17 per cent diopside crystals and 83 per cent liquid of composition *G*. At this temperature bytownite of composition *H* (approximately Ab_1An_4) begins to crystallize and the composition

of the liquid changes along the boundary curve *DE* toward *D*. Both diopside and plagioclase continue to separate, and the plagioclase crystals, not only those separating at any instant, but also those which had formerly separated, continually change in composition, becoming richer in albite. At 1220° the whole mass is made up of 37 per cent diopside crystals, 25 per cent labradorite crystals of composition *L* (Ab_1An_2), and 38 per cent liquid of composition *K*. As the temperature falls still lower the liquid gradually decreases in amount and continually changes in composition until at 1200° it is all used up, the last minute quantity having the composition *M*. In the meantime diopside and plagioclase crystals have been separating, and the plagioclase has been changing continuously in composition until at 1200°, when the last of the liquid disappears, the composition of the feldspar is Ab_1An_1. The whole mass now consists of 50 per cent diopside and 50 per cent Ab_1An_1.

Crystallization takes place according to the foregoing outline if no sinking of crystals occurs. If diopside crystals sink, no effect on the composition of the liquid results. We should have then at 1220° a mass in which the diopside crystals were of increasing concentration toward the bottom, and in which a certain upper portion was free from diopside crystals, consisting of 60 per cent of liquid of composition *K* and 40 per cent labradorite crystals of composition *L* (Ab_1An_2). Let us imagine that at this stage appreciable sinking of plagioclase crystals begins, and that it increases in importance as the liquid changes toward *M*, and therefore becomes lighter. It is necessary to imagine also that the plagioclase crystals sink very slowly, and are outstripped by the heavy diopside crystals which are forming simultaneously and which increase in size more rapidly since the liquid is becoming relatively impoverished in diopside. It seems possible, then, that, locally at least, plagioclase crystals might accumulate in a mass free from diopside crystals and containing only a little interstitial liquid whose composition would lie between *K* and *M*. If the mass had 20 per cent interstitial liquid of composition *V* and 80 per cent crystals slightly more calcic than Ab_1An_1, the final rock formed on solidification of the interstitial liquid would consist of 95 per cent Ab_1An_1 and 5 per cent

diopside (J). If the mass had only 10 per cent interstitial liquid of composition W and 90 per cent crystals slightly more calcic than Ab_1An_1, the final rock would consist of 98 per cent Ab_1An_1 and 2 per cent diopside (Z). This degree of concentration of plagioclase is ample for the production of nearly all anorthosites, and is more than sufficient for most of them. To understand the formation of anorthosites of extreme purity it is necessary to follow what has been happening to the liquid in the meantime, that is, to that part of the liquid from which crystals have subsided. Instead of becoming completely crystalline when the composition M is attained, it continues to change its composition toward S and may go even beyond S, that is, it becomes very rich in albite (haplo-syenitic)[1] and the diopside becomes a vanishing quantity. Now it can be considered that locally the interstitial liquid occurring between the plagioclase crystals was of this type, which it might be if the rate of interchange of material did not quite keep up to equilibrium requirements, a very likely possibility. On complete solidification of such a mass anorthosite of extreme purity would result. This would be more likely to give a rock made up of acid labradorite or even of andesine-labradorite. It is because plagioclase crystals may accumulate, under certain circumstances, in a liquid which is itself nearly pure plagioclase (though very different from the crystals in composition) that we can get plagioclase rocks of such extreme purity.[2] For the case of natural rocks the interstitial liquid is enriched, not merely in albite, but also in orthoclase and to some extent in quartz. In those anorthosites that run very low in bisilicates we therefore commonly find 5 per cent or more orthoclase, and occasionally some quartz.

In the foregoing the writer has done his best to picture a process whereby plagioclase crystals may accumulate in sufficient force to give a mass of anorthosite. Unquestionably there are some difficulties, the gravest being that connected with the nearly complete sorting of plagioclase and pyroxene, whose periods of crystal-

[1] N. L. Bowen, "The Crystallization of Haplobasaltic, Haplodioritic and Related Magmas," *Am. Jour. Sci.* (4), XL (1915), 161.

[2] Another possible method of obtaining extreme monomineralic composition is suggested later (p. 238).

lization are in large part contemporaneous. If one could assume that plagioclase follows pyroxene in the crystallization of gabbro, as some geologists appear to do, the sorting would be a simple matter, but chemical considerations will not permit such an assumption. Yet the difficulties do not seem insurmountable, especially in comparison with those connected with other processes. Diffusion is hopelessly incompetent even if it is assumed that its tendency is in the proper direction. Liquid immiscibility, whose operation in the case of silicates has nothing to support it, would certainly not tend to produce pure liquids in any case, but only to produce liquids of contrasted composition, all being, nevertheless, mutual solutions of minerals. Added to these is the temperature objection to which reference was made on an earlier page, and still others might be mentioned. On the other hand, it does seem reasonably probable that a mass of gabbroid magma might cool sufficiently slowly to permit the necessary amount of sorting of crystals especially if it was a large mass, or if it was very deeply buried.

CHARACTERISTICS OF ANORTHOSITE CONSEQUENT UPON THE SUPPOSED METHOD OF FORMATION

It must be admitted, however, that opinion as to whether the process can take place is not a very decisive matter. More important is the deduction of its consequences followed by a survey of the characteristics of anorthosites in order to determine to what extent they agree with the requirements. If anorthosites are generated only by the accumulation of crystals, then the more nearly a rock mass approaches an exclusively plagioclase composition, the more nearly it should have approached the completely solid condition when that composition was attained. In discussing artificial melts we have seen that if we have a portion with 80 per cent plagioclase crystals and 20 per cent interstitial liquid it would, on crystallization, have 95 per cent plagioclase and 5 per cent diopside. In other words, a rock containing only 5 per cent diopside could have had, after that total composition had been attained by the process we are considering, not more than 20 per cent liquid. A rock containing 10 per cent diopside could have had a maximum of 35 per cent liquid, and one containing only 2 per cent diopside

could have had not more than 10 per cent liquid. For natural melts the figures would not be the same, and the probability is that the amount of liquid would be relatively somewhat larger on account of the presence of orthoclase in the liquid. Assuming the figures to be approximately the same, it seems necessary to believe that a rock containing 95 per cent or more plagioclase, if it is true that it is formed by the method outlined, should exhibit certain characteristics that set it apart from such a rock as a granite, which, as we know well enough, often occurs in the completely molten condition. When the plagioclase rock is formed *in situ*, it need exhibit no features differentiating it from other igneous rocks except perhaps a marked coarseness of grain. Such a body, while still containing nearly its maximum of about 20 per cent interstitial liquid, might be moved *en masse*, though probably not far, from the position of its original formation, but this movement would be accompanied by the development of protoclastic structure, especially about the margins. Since all crystalline igneous rocks pass through a stage at which they are 80 per cent crystalline, all are subject to the possibility of the development of similar structures under parallel conditions. The plagioclase rock differs only in that it cannot be moved without developing this structure, since if moved when containing more than 20 per cent liquid the mass moved has not yet attained the requisite degree of concentration of plagioclase crystals. Protoclastic structure and granulation should therefore be perfectly general features of all moved anorthosite masses and very common features of all anorthosites.

When we come down to the movement of such material in small masses, it seems impossible that it would be capable of being injected into small openings in cold country rock—in other words, that it would form no small dikes in such rocks, though it might occur as dikelike masses in consanguineous igneous types, being injected into them at a time when they themselves were not completely crystalline. Such material should, moreover, be incapable of occurring as effusive flows.

For the purposes of the foregoing discussion a mass containing 20 per cent interstitial liquid has been arbitrarily chosen. It is a matter of opinion how much liquid a mass must have in order to

be injected as small dikes. If it is considered that about 50 per cent liquid is necessary, then only anorthosite or, better, anorthosite-gabbro, with about 85 per cent plagioclase could occur as small dikes. If somewhat less than 50 per cent liquid is necessary, then a rock somewhat richer in plagioclase could occur in that manner. In the case of effusive masses, if it is considered that more than 50 per cent liquid is normally requisite for their formation, only anorthosites with less than 85 per cent plagioclase could occur as effusives.

A study of the literature of anorthosites from various localities seems to show that, in so far as published descriptions are concerned, anorthosites do have substantially the characters outlined in the foregoing discussion, which is based on the hypothesis that they are accumulated masses of plagioclase crystals. Still the idea is rather novel, and probably no one had such a hypothesis in mind when examining anorthosites, so that, while many observations bearing directly on the problem are recorded, one might readily believe that perhaps many others equally pertinent escaped record. For this reason the writer spent a few weeks in the Adirondack area and in the Morin area of anorthosites, becoming acquainted at first hand with the relations there found. Attention was confined almost entirely to parts already mapped in detail so that a maximum could be seen in the limited time. The facts bearing on the origin of anorthosites in these areas will be stated principally as recorded by others, and only to a very limited extent supplemented by this brief personal experience. It is desired to express thanks to Professors Kemp, Cushing, and Adams and to Mr. Dresser for interest taken and for furtherance of the work in various ways.

THE ADIRONDACK ANORTHOSITE

General relations.—The anorthosite of the Adirondacks occurs principally as a single great area, for the most part in the heart of the mountains and making up its highest peaks, though extending eastward to the lower country in the vicinity of Lake Champlain. The mass occupies an area approximating 1,200 square miles, the principal constituent of the rock throughout this area being plagioclase. Large exposures may be made up almost exclusively

of plagioclase, while other exposures, perhaps equally general and widespread, would average nearly 10 per cent bisilicates. This latter type seems to prevail even in the heart of the area being represented in most of the exposures of the Keene Valley, while the bare ledges of the summit of Mt. Marcy average probably more than 5 per cent bisilicates. Toward its borders, too, the anorthosite commonly passes into anorthosite-gabbro and gabbro. Nevertheless, the mass as a whole is aptly described as consisting of "little else than feldspar which is generally a blue labradorite."[1] If this great mass, whose volume is to be measured in thousands of cubic miles, was ever molten as such, it is remarkable that none of the many investigators who have studied the area have found a single dike consisting of nearly pure plagioclase in the surrounding rocks. The evidence of the intrusive nature of anorthosite in its more typical development depends on the occurrence of Grenville inclusions in it. To be sure, the anorthosite is nearly always immediately surrounded by a younger rock, the syenite, but in several localities the invading power of certain phases of the anorthosite mass is well shown. Anorthosite-gabbro invades the Grenville and associated older gneisses in places, and occurs as outlying masses upward of 20 miles distant from the main anorthosite mass. As soon, then, as the bisilicates mount to 20 or 25 per cent there is no lack of evidence of the power of the mixture to penetrate into openings in the surrounding rocks. The great mass of the anorthosite itself contains much fewer bisilicates, yet in spite of the overwhelming volume of such material it is entirely unrepresented as dikes and small intrusions. It seems to be a reasonable conclusion that this material was incapable of being injected into the older rocks.

Intimate relation of syenite and anorthosite.—The anorthosite core of the Adirondack igneous mass is surrounded practically everywhere by the syenite-granite series with which are associated numerous areas of Grenville sediments and perhaps older granite gneiss. There has been a considerable tendency to consider the syenite-granite as an igneous unit and anorthosite as a separate unit. This tendency has been emphasized perhaps by the fact

[1] D. H. Newland, *N.Y. State Museum Bull. 119*, 1908, p. 17.

that in one locality, in the vicinity of Long Lake, Cushing was able to demonstrate that the syenite is younger than the anorthosite. Yet even Cushing states: "The syenite and anorthosite seem surely derivatives from the same parent magma and of no great difference in age."[1] This aspect of the anorthosite, i.e., its intimate connection with the syenite, is emphasized in the area as a whole, where, in spite of fairly good exposures, only one other locality showing the intrusive relation of syenite to anorthosite has been found, but where, on the other hand, types intermediate between the two are rather commonly found. This feature of Adirondack igneous geology has not been studied in detail except, apparently, at the one locality in the Long Lake quadrangle, though it appears to deserve such study since it marks the great similarity between the Adirondack anorthosites and others, the Norwegian and Volhynian occurrences, for example. In the writer's limited experience it was found that the change from anorthosite to syenite was heralded by the appearance of inclusions of potash feldspar in the plagioclase. The inclusions are small patches, uniformly oriented and constituting therefore an antiperthite.[2] These inclusions often show a rather peculiar feature which, so far as the writer is aware, has not been noted elsewhere. Surrounding some of them and corresponding in general though not in detail with the outline of the inclusion is an area of plagioclase differing from the crystal as a whole. Its outline is usually sufficiently sharp to make it possible to determine that it has a slightly higher refractive index than the rest of the plagioclase, besides a different position of extinction which makes it a rather conspicuous feature. An extremely fine twinning, not shown by the main body of the plagioclase crystal, can usually be seen with high magnification. A suggested explanation of these features is that the material of the microcline inclusions was originally in solid solution in the plagioclase and that on separating from solid solution it left the plagioclase poorer in potash feldspar, and therefore of higher refraction than the general body of the crystal more remote from the inclusions. But the rims about the inclusions usually have not much greater mass than the inclusions

[1] *Bull. Geol. Soc. Am.*, XVIII (1907), 485.

[2] F. E. Suess, *Jahrb. K. K. geol. Reichsanst.*, LIV (1904), 417–30.

themselves, and it would be necessary for the surrounding plagioclase to have contained originally nearly one-half potash feldspar, which it certainly did not. It seems more likely that the potash feldspar, though occurring as definite inclusions, was, nevertheless, formed from the portion which remained liquid last and was introduced into the plagioclase by a sort of replacement, the change in the plagioclase aureole being an effect going hand in hand with this replacement.

With the microcline inclusions some interstitial microcline generally makes its appearance, and this may increase in amount until it becomes an important constituent of the rock. In such a specimen the plagioclase is usually andesine rather than labradorite, though the large blue labradorites typical of the anorthosites often occur as phenocryst-like individuals. The rock is definitely intermediate between anorthosite and syenite, though the microcline, in the few slides examined, has not as marked a tendency to be perthitic as it has in the typical syenite. One sees these intermediate types in some of the exposures about the shores of Lake Placid. There is apparently a transition between some of the rocks mapped as gneiss (syenite-granite) and those mapped as anorthosite in that vicinity.[1] Similar intermediate types are found in the vicinity of Elizabethtown, and as a whole they seem to be closely analogous to the perthitophyres of Volhynia as described by Chrustschoff,[2] and to the Norwegian monzonites described by Kolderup.[3]

An interpretation of the structural relations of syenite and anorthosite.—While the anorthosite and syenite are evidently closely related and connected by transitional types, they are usually very distinctive. There is one aspect of their field relations in which they are strongly contrasted and with which the writer was impressed in the field. In the great area of syenite-granite that surrounds the anorthosite core, areas of Grenville are exceedingly numerous. In many of the mapped quadrangles it has been neces-

[1] Map accompanying report by Kemp, "Geology of the Lake Placid Region," *N.Y. State Museum Bull. 21*, 1898. Since the above was written the writer has been informed by Professor William J. Miller that, while the transitional relation is shown, the syenite also sends dikes into the anorthosite.

[2] *Tschermak's Min. Petr. Mitt.*, 9 (1888), p. 470.

[3] *Bergens Museums Aarbog*, No. V (1896), p. 86.

sary to use a color to represent a mixture of Grenville and syenite that defies separate mapping. Now the manner of occurrence of the Grenville when found in considerable areas is commonly as a roof lapping over the syenite and showing only comparatively moderate dips. One sees this in typical form on the shores of Lake Champlain immediately north of Port Henry, and Miller has recently described this relation in widely scattered Adirondack localities, the large-scale example in the Blue Mountain quadrangle being of special interest.[1] Syenite and Grenville in this relation are almost constant companions.

The anorthosite areas, on the other hand, are very different. It could be said with little exaggeration that on passing the borders of the anorthosite core one encounters only anorthosite. It is true that inclusions of Grenville have been found, enough to prove the intrusive nature of the anorthosite, but these appear to be small completely inclosed blocks and do not suggest actual roof remnants. In spite of their occasional occurrence the contrast between the syenite and anorthosite areas is very striking. One has but to glance at the maps of such areas as the Paradox Lake and Long Lake quadrangles to be convinced of it. Not only is the anorthosite unbroken by areas of Grenville, especially away from the margins, but it is likewise practically free from protrusions of the syenite, although the syenite is, as we have seen, in part at least, a later rock. If one pictures the syenite and the anorthosite as conventional batholiths, some difficulty is experienced in accounting for the foregoing facts. It is necessary to imagine an early intrusion of a huge plug of anorthosite followed by an intrusion of syenite which took the form of a hollow cylinder circumscribing it and invading it only peripherally. All of this must take place without throwing the Grenville series into appressed folds, indeed, without very significant folding of any kind. It is then necessary to imagine that erosion removed every vestige of a roof from the small interior anorthosite area, and left great stretches of it throughout the broad syenite-granite belt that surrounds it.

All of this is perhaps possible, but at the same time seems highly improbable. On the other hand, if one pictures the Adirondack

[1] William J. Miller, *Jour. Geol.*, XXIV (1916), 591.

complex as essentially a sheetlike mass with syenite overlying anorthosite, the facts of Adirondack igneous geology seem to arrange themselves more rationally. On this supposition one would expect to find areas of the Grenville roof covering the syenite in places and to find it relatively little disturbed. In the interior and

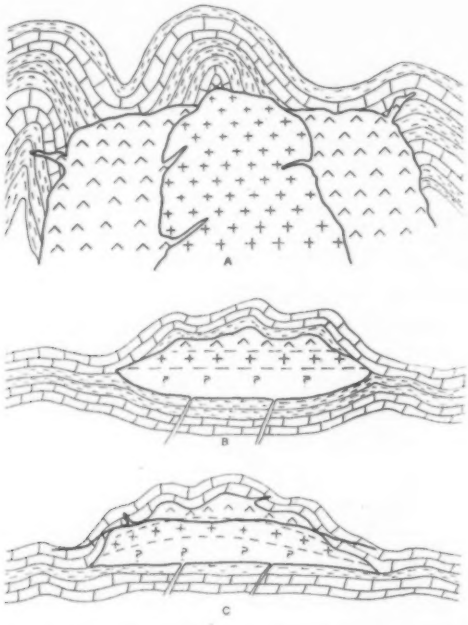

FIG. 2.—A. Adirondack complex interpreted as batholitic. +Anorthosite, ^Syenite
B. Adirondack complex interpreted as laccolithic (undisturbed)
C. Same as B after disturbance. Heavy line indicates erosion surface

eastern region of maximum uplift one would expect to find the deeper-seated anorthosite laid bare and to find it free from areas of the roof since it was for the most part separated from the roof by a layer of syenite. (In Fig. 2 the alternative interpretations of the Adirondack complex are presented.)

On this supposition of the origin of syenite and anorthosite by gravitative differentiation of a sheetlike mass it is by no means

necessary that syenite and anorthosite should always grade imperceptibly the one into the other. The Adirondack area is one of considerable disturbance. It no doubt suffered some disturbance at the time of the intrusion of these igneous masses, and it has unquestionably been much faulted since their consolidation. Is it reasonable to suppose that the region necessarily stood stock-still during the long period required for the consolidation of these igneous masses? It is, in fact, likely that faulting took place during this period as well, and if it occurred at a time when the anorthosite was completely crystallized but the syenite still molten then it is quite possible that syenite might thus be brought laterally against, and acquire an intrusive relation to, anorthosite. The fact that syenite invades anorthosite locally need not therefore be fatal to the conception of gravitative differentiation of these two types, nor does it necessarily indicate the order of their arrival from the depths. A diagrammatic simplicity is not to be expected, but the broader relations, including the substantial freedom of the whole interior of the anorthosite area from protrusions of syenite, seem to give a distinct preference to their arrangement substantially as layers with the syenite above as outlined in the foregoing.[1]

The writer's leaning toward differentiation practically in place as the explanation of the variation of many batholiths has been criticized publicly by Harker,[2] and by others in private correspondence. It is apparently believed that when one rock invades another the relation necessarily means that the invading rock arrived from a deep-seated magma basin subsequent to the other. This may be quite true, as a rule, but there is little evidence in most cases that adequate consideration has been given to the alternative view of differentiation practically in place with only relatively minor disturbance during the magmatic period. The petrologist should be reluctant to reject this possibility without fair trial, for he destroys some of the hope of solving the problems of igneous

[1] A few small patches of syenite have been found within the anorthosite area. If these are regarded as having been pushed up from below as pipes, it is rather remarkable that in no instance has their intrusive nature been demonstrated. On the other hand, if they are remnants of an overlying syenite, they might well lack a definite intrusive character.

[2] *Jour. Geol.*, XXIV (1916), 554.

geology by thrusting the locus of differentiation ever backward into unseen depths. The Adirondack intrusives would, it is felt, be interpreted by many in the conventional manner, and for this reason some pains have been taken to present the alternative view.

Daly regards the Adirondack anorthosite-syenite complex as probably a laccolith. According to his views anorthosites are formed in laccoliths because those masses suffer little contamination from wall-rock material and anorthosite is a pure differentiate of gabbro magma. A certain amount of assimilation of wall rock can occur, however, without eliminating the possibility of the formation of anorthosite, and under such circumstances the syntectic magma differentiates in such a manner that syenite is formed. In batholiths, on the contrary, whose emplacement takes place by stoping, the consequent assimilation has so important an effect on the gabbroic magma that no anorthosite is formed, according to Daly. The writer's interpretation of the Adirondack complex as a stratified, sheetlike mass with a lower layer of anorthosite and an upper layer of syenite intimately associated with the Grenville sediments is therefore in striking agreement with Daly's conception. However, a consideration of crystallizing magmas in the light of experimental study compels the writer to believe that there would exist in association with the anorthosite a mass of syenite, even if the invaded rocks were of infinitely refractory and inert materials. The mass of syenite was probably augmented by assimilation of foreign rocks, but that is a different matter. Apparently this opinion is in accord with the conclusions of those best acquainted with the Adirondack rocks in the field who, while demonstrating that assimilation takes place, consider it rather as an incident than as a fundamental factor controlling the genesis of rock types. And, again, the writer's interpretation of the igneous mass as sheetlike is offered merely because of the difficulty of picturing the general relations otherwise. Indeed, it is not considered that the Adirondack batholith or laccolith or whatever it may be called, is exceptional in this respect. Most batholiths are regarded by the writer as just such masses. Consequently it is believed that the shape of the intrusive is not the determining factor in the formation of

anorthosite. It is rather a balance between density, rate of cooling, and viscosity such that the necessary amount of sorting of crystals occurs.

The writer must confess an inability to state precisely the reason why the species presented in an igneous sequence at one locality may be different from those at another. It is nevertheless believed that it is unnecessary that the original magmas need have been different, or even that the manner of differentiation need have varied. The results seem to be possible if there was a variation in the extent to which separation of crystals from liquid and also sorting of individual minerals were able to take place. Variations in these factors depend on physical conditions which have, however, their chemical consequences, for the removal or non-removal of a crystal has each a perfectly definite effect on the future course of the liquid.

In one sequence, which is well shown in the pre-Cambrian of Ontario and in certain British intrusives, there is practically only gabbro and granite with little that could be described as intermediate. Apparently this is especially likely to be true of masses of moderate size. In somewhat larger masses ultrabasic rock may make its appearance as one of the members with occasionally some anorthosite. Usually for the formation of anorthosite a very large mass is necessary, and possibly also a deep-seated mass. On the other hand, for the formation of those sequences that emphasize intermediate types such as diorite, quartz diorite, and granodiorite the indications are that very large masses are necessary, but that they should probably occur at moderate depths. There is nothing here in the way of hard and fast rules, but there do seem to be fairly definite tendencies. All of these are reasonably to be considered the result of differences of the physical conditions under which cooling took place.

THE MORIN ANORTHOSITE

General features.—The Morin anorthosite area of Canada is in many respects very like the Adirondack area. It lies near the edge of the great pre-Cambrian shield where it is overlapped by Paleozoic rocks. It covers a territory of about 1,000 square miles which, while not as mountainous as the Adirondacks, is nevertheless quite

rugged, many of the important elevations of the Laurentian Mountains of that region lying within the boundaries of the anorthosite mass. As with the Adirondack Mountains, the Laurentian Mountains have suffered glaciation and lakes abound, with the result that even in the matter of popularity as a summer resort the two regions are alike, the Laurentian region drawing a plentiful supply of tourists on account of its proximity to the Canadian metropolis. Coming to the more fundamental matters of geologic structure and petrography we find again a remarkable degree of similarity to which attention is directed in the sequel.

An area of more than 3,000 square miles comprising the Morin anorthosite was mapped nearly thirty years ago by F. D. Adams, and a map published on a scale of four miles to one inch.[1] The map is therefore not as detailed and does not form as useful a guide for one who would see a great deal in limited time as do the quadrangle maps of the New York State Museum, which are the result of the labors of a number of workers. On the other hand, the text of the report is full of minute descriptions of localities, and a brief visit was paid to some of these in order to become familiar with them at first hand.

Relation of anorthosite to the surrounding rocks.—The Morin anorthosite occurs, as does that in the Adirondacks, principally as a single, great intrusive mass. There is, however, a greater number of small outlying masses that give the area a somewhat greater interest with reference to the problem of the origin of anorthosite. The associated rocks are practically identical with those in the Adirondacks, consisting of igneous gneisses largely of salic composition and of sediments of the Grenville series. Of all these Adams concluded that the anorthosite was the youngest, a relation which he appears to have considered a general one for the Canadian anorthosites including the great Saguenay mass. Recent study of the Saguenay area has shown, however, that there are associated with the anorthosite certain more salic types, possibly consanguineous with it, but of somewhat later age,[2] the whole being appar-

[1] "Geology of a Portion of the Laurentian Area North of the Island of Montreal," *Geol. Surv. Can. Ann. Rept.*, Vol. VII, Part J, 1896.

[2] Personal communication from Mr. Dresser.

ently a counterpart of the anorthosite-syenite association in the Adirondacks.

While the writer has nothing very definite to offer concerning a similar association in the Morin area, certain indications were found tending to show that detailed study might definitely bring out its existence there. In the vicinity of Piedmont and extending southeastward beyond Shawbridge the gneiss which here forms the southern boundary of the anorthosite mass is a rather fine-grained greenish rock looking very similar to the syenite of the Adirondacks. Specimens of this taken at various distances from the borders of the anorthosite show that it varies considerably. In all cases the rock is composed principally of plagioclase but, on receding from the border of the anorthosite, orthoclase continually increases in importance. There is apparently a perfect transition from anorthosite toward syenite, though in none of the specimens collected had the change gone to completion, that is, none of the specimens could be called typical syenite. In one specimen, however, orthoclase made up about 30 per cent of the rock, and was accompanied by some quartz, so that probably the change would not have to be followed much farther to afford typical syenite.[1] On account of this transitional relation it is very difficult, at least where seen by the writer, to fix a boundary between anorthosite and gneiss. Specimens that are apparently typical anorthosite and taken well within the boundary of the mass as mapped by Adams, are found to be like those types of anorthosite of the Adirondacks which show the beginning of transition to syenite in that the plagioclase contains orthoclase inclusions. Specimens from the cliffs north of Piedmont station show the orthoclase in streaks forming an antiperthite much richer in orthoclase than any seen in Adirondack specimens.[2] Even specimens taken four miles within the border of the anorthosite, in the village of Ste. Adèle, show abundant orthoclase inclusions in the plagioclase.

[1] Professor Adams informed the writer in conversation that intermediate monzonite types analogous to the Norwegian types of Kolderup occur in the region, so that, while they are not described at length in his report, he undoubtedly recognized such types.

[2] In none of the Canadian specimens was there seen any peculiar zone of plagioclase surrounding the orthoclase inclusions as described from the Adirondack localities.

In the vicinity of Piedmont occasional dikelets are seen cutting the anorthosite, which are found to consist principally of microperthite with some quartz and an unusually large amount of magnetite, a composition that suggests a syenitic source. Taken all in all the evidence favors the possibility that we have in the Morin area syenite and anorthosite related in the same manner as in the Adirondacks, in part transitional into each other, but the syenite of somewhat later consolidation. Even in the matter of the occurrence of a certain aberrant type the two regions show a further similarity. In the vicinity of Elizabethtown, New York, there is a peculiar dark rock resembling a basic syenite, but containing phenocrysts of the blue labradorite which is described by Kemp as the Woolen Mill type.[1] This rock is duplicated in both megascopic appearance and microscopic characters in exposures in the streets of the village of St. Jérome, Quebec. It is apparently intimately related to both syenite and anorthosite.

Concerning the structural relations of syenite-granite and anorthosite it is impossible to say anything definite, since syenite that may be regarded as probably related to the anorthosite has not been delimited. About twenty miles east of the anorthosite mass, syenite-granite makes its appearance from beneath the flat-lying gneiss of the surrounding country. Adams considers that the syenite is much more widespread, the gneiss of the surrounding area forming merely a relatively thin and little disturbed roof over it. If the anorthosite is, as in the Adirondacks, a deep-seated portion of the same igneous complex, then in order to bring the anorthosite and the roof gneiss into lateral juxtaposition a considerable movement would be necessary, and it is found that, after passing westward over a twenty-mile stretch of little disturbance, the gneiss is then, on approaching the anorthosite, thrown into sharp folds.[2] Moreover, we find on passing within the border of the anorthosite mass that the typical roof gneiss with its occasional bands of limestone is absolutely lacking, a fact that suggests that the roof gneiss was nowhere superposed directly upon the anortho-

[1] "Geology of the Elizabethtown and Port Henry Quadrangles," *N.Y. State Museum Bull. 138*, 1910, p. 35.

[2] Adams, *op. cit.*, pp. 11 and 12.

site. Not impossibly, then, there may be in the Morin area a stratified mass, made up of syenite above and anorthosite below, with general relations similar to those we have imagined to exist in the Adirondacks.

Lack of mineralizers in the Morin anorthosite.—On an earlier page it was pointed out that there is in anorthosite no supply of minerals other than plagioclase adequate to produce significant lowering of the melting temperature of the plagioclase. Anorthosite could exist as magma, therefore, only at very high temperatures unless there was present a proportion of volatile components sufficient to produce great lowering. Adam's work on the Morin anorthosite appears to give a definite negative answer to this possibility. The minerals normal to the anorthosite are those commonly believed to form from relatively anhydrous melts. The ferromagnesian material appears typically as pyroxene, not as hornblende or mica. There is little if any tendency for the pyroxene to be made over into hornblende or mica even in the very latest stages of crystallization when the volatile components would reach their maximum concentration. Even intense shearing of the rock, which took place partly during this latest stage of crystallization and partly immediately subsequent thereto, had no tendency to develop hornblende and mica from the pyroxene, though under such conditions it is well known to be particularly susceptible to this change if there are mineralizers present in significant quantity.

All of the evidence points to a substantial lack of mineralizers. The Morin anorthosite is in these, as in most respects, typical of the world's anorthosites. We are therefore impelled toward the belief that, inasmuch as anorthosites show no definite high-temperature characters, they are preferably to be considered as never having been molten as such.

Anorthosites as small intrusions.—In considering the physical condition of the anorthosite as bearing on this question of its origin it is perhaps well to recall the circumstances under which Adams' investigation was undertaken. Prior thereto there had been a common tendency to believe that all banded rocks were of sedimentary origin, and since the anorthosite is often markedly banded it had been regarded as a member of the sedimentary series with

which it is associated. Adams entered the field as the champion of the newer conception that many banded gneisses are of igneous origin, and that of these the anorthosite was a prominent representative. Under such circumstances it cannot be questioned that any geologist would search diligently for dikes and tongues of anorthosite running out into the surrounding rocks, and that having found them he would not fail to record them. Yet one will search Adams' report in vain for a single instance of such a dike. The wording of the one statement which is an apparent exception serves only to emphasize the truth of the above. The anorthosite mass is described as "sending *an apophysis*" into the surrounding gneiss.[1] The apophysis referred to is a great armlike extension five miles wide. Attention is directed to this lack of dikes in order to emphasize that here we have an intrusive of a peculiar character, not to call in question the interpretation of the anorthosite as an intrusive. Of that there can be no question. Dikes intimately related to the anorthosite do occur, but they serve to emphasize the more that there are none consisting almost entirely of plagioclase, though there is mile upon mile of such rock within the main body of anorthosite. It seems reasonable to conclude, therefore, from the evidence in the Morin area, that a rock consisting almost entirely of plagioclase is incapable of being injected as dikes. The reason for this is to be found, it is believed, in the manner of its origin, a mass of anorthosite being merely a collected mass of plagioclase crystals.

There are, as has been stated, several small outlying masses of anorthosite besides the great central mass. These are listed and described in detail by Adams. Some of them were visited by the writer, but nothing need be added, indeed nothing can be added, to Adams' statements, which are quite explicit with reference to the point that it is desired to emphasize. In discussing the anorthosite of the outlying masses in general he states: "It is perhaps on the whole richer in iron magnesia constituents and often contains minerals such as hornblende and biotite."[2] Statements of like import are made in discussing the bands severally. Of the Kildare

[1] *Op. cit.*, p. 116. Italics are the writer's. [2] *Ibid.*, p. 117.

bands he says: "The rock is on the whole richer in bisilicates than the Morin anorthosite, approaching more nearly a normal gabbro or norite in composition."[1] Practically the same statement is made of the Cathcart bands;[2] and again of the Brandon bands he says: "Like most of the small anorthosite bands described in this report, these from the township of Brandon are usually richer in bisilicates than a true anorthosite should be."[3]

Apparently, then, these outlying bands always vary from typical anorthosite, usually toward gabbro, but in one or two instances perhaps the variation is toward syenite-granite, as suggested by a content of hornblende and biotite. The bands are by no means inconsiderable bodies, usually having a width of upward of half a mile or more and a length of several miles. Even masses of this size are apparently never made up of nearly pure plagioclase rock, a fact that accords with the belief that a fair proportion of other minerals is necessary before anorthosite acquires appreciable invading power in masses of limited size.[4]

CONSIDERATION OF ANORTHOSITES IN GENERAL

The agreement of the two most completely described areas of anorthosite on the North American continent with the consequences of the hypothesis of the origin of anorthosite is apparently rather good. The Norwegian and the Russian areas are equally significant, but no attempt will be made to discuss them in detail. Reference will be made, however, to the schematic presentation of differentiation given by Kolderup, which is based entirely on field evidence, and of which a copy is presented below. Attention is called to the central position of the norite with its anchimonomineralic basic differentiates and its more complex acid derivatives. These are, it is believed, the accumulations of sorted crystals on the one hand, and the residual liquids on the other.

[1] *Ibid.*, p. 122. [2] *Ibid.*, p. 124. [3] *Ibid.*, p. 126.

[4] A dike of anorthosite in the Cripple Creek country, to which the writer's attention was called by Professor Graton as an apparent exception, is described as containing biotite and quartz. It evidently varies toward granite, and its occurrence as a dike might reasonably be expected.

KOLDERUP'S REPRESENTATION OF DIFFERENTIATION IN THE EKERSUND-SOGNDAL ANORTHOSITE AREA

Bronzite granite
|
Adamellite
|
Banatite
|
Monzonite
|
Quartz-norite
|
Gabbro-norite—Norite—Anorthosite-norite—Anorthosite
|
Bronzitite—Norite-bronzitite
|
Ilmenite-norite
|
Ilmenitite

Kolderup's anorthosites become more basic and schistose toward their borders and their contact relations are obscure. One cannot be sure from his text whether there are small dikes of anorthosite in the surrounding rocks or not, but apparently there are not.[1]

Apophyses consisting of 95 per cent basic labradorite and 5 per cent augite cut the Sooke gabbro of Vancouver Island described by Clapp.[2] The anorthosite veins and the gabbro are consanguineous, however, and the former with, say, 20 per cent liquid might have been squeezed into the not completely crystallized gabbro mass, the process involved being then rather different from that occurring in the injection of anorthosite into cold country rock.

Dikes of anorthosite are described as cutting the older rocks in the Rainy Lake region, but one cannot be sure from the description whether the dikes are strictly anorthosite or rather the related anorthosite-gabbro.[3] And so it is with many descriptions. It is profitless, therefore, to pursue the discussion of various anorthosite occurrences further since they were not examined with the questions

[1] "Die Labradorfelse des westlichen Norwegens," *Bergens Museums Aarbog*, No.V (1896), p. 14.

[2] C. H. Clapp, "Southern Vancouver Island," *Geol. Survey Canada Mem. No. 13*, 1912, p. 116.

[3] Since the above was written Professor Coleman has informed me that in so far as he can recall there are no dikes of typical anorthosite.

raised in mind. An individual cannot do more than state the problem and leave its suggested solution to confirmation or refutation at the hands of those acquainted with various anorthosites in the field.

Of anorthosite in general it can be said, however, that no effusive equivalent has hitherto been found anywhere. This must be regarded as a very surprising fact if there were ever masses of molten plagioclase adequate to furnish such great exposures of anorthosite as occur in various parts of the earth. On the other hand, if these anorthosite masses were merely collections of plagioclase crystals effusive anorthosites are scarcely to be regarded as possible.

MONOMINERALIC ROCKS IN GENERAL

Enough has been said incidentally in the foregoing to make it clear that the problem of any monomineralic rock is, in its essentials, the same as the problem of the anorthosites. There are no more promising methods of obtaining pure molten olivine or pyroxene than there are of obtaining molten plagioclase. On the other hand, the collection of crystals to give substantially solid masses of nearly pure olivine or pyroxene does not seem out of the question.

A survey of the domain of igneous geology lends considerable support to the possibility that peridotites and pyroxenites are so generated. In making the test of their occurrence as small dikes we find that this is perhaps the most characteristic manner of occurrence of peridotite, but on closer examination it appears that this fact may be due rather to the elastic nature of the term peridotite, which may be applied to a rock containing considerable plagioclase, pyroxene, hornblende, or mica, or all of these, as well as its olivine. Typical dunite, or nearly pure olivine rock, however, probably does not occur as dikes, if we except, again, its occurrence in such form in closely related and essentially contemporaneous igneous rocks. The same statement may be made of rock types excessively rich in pyroxene. As to the question of their occurrence as effusive types it is found that peridotite has an effusive equivalent in picrite, but picrite is far from being a pure olivine rock. Dunite itself has apparently no effusive equivalent. With the

pyroxenites the case is apparently the same. Limburgite and augitite can scarcely be regarded as monomineralic rocks in the stricter sense of the term, and that is the only sense in which it can be used in testing the hypothesis. The presence of both pyroxene and olivine, of a glassy base and usually of some feldspathoid makes it clear that these effusive pyroxenites do not constitute an exception to the rule that the monomineralic rocks do not have effusive equivalents. Apparently, the facts are in accord, therefore, with the hypothesis that monomineralic rocks are accumulated masses of crystals.[1] Mention may be made again here of Vogt's discovery that the richer a peridotite is in olivine, the richer the olivine is in magnesia, a fact which is readily explained on the assumption that peridotites are made up of accumulated early crystals.

All of the monomineralic rocks often do occur, however, in a manner which has led a very great number of investigators to speak of the magmas of these rocks as freely as of the magmas of any others. This is probably due partly to the fact that the possibility of their origin after the manner here advanced did not occur to the investigators, but whether this was always the case is a question that, again, an individual cannot answer. One of the most remarkable occurrences of anchi-monomineralic rocks, especially pertinent in the present connection, is that described by Harker from the islands west of Scotland. As a result of his minute descriptions an especially favorable opportunity is offered of discussing these rocks in the light of the present conception of the origin of monomineralic rocks. The rocks are intricately banded in such a manner as to lead Harker to suggest the intrusion of a non-uniform magma, implying apparently a non-uniform liquid.[2] A difficulty in the way of accepting this interpretation is that connected with obtaining a non-uniform liquid, especially with

[1] While it has been necessary in applying the foregoing tests to set aside anchi-monomineralic rocks containing a considerable amount of other minerals, it should not be assumed that there is any essential difference in the method of formation. These are merely examples in which accumulation of crystals of one kind has not taken place to quite the same degree and which consequently could have had a considerable amount of interstitial liquid.

[2] "Geology of the Small Isles of Inverness-shire," *Mem. Geol. Survey Scotland*, 1908, p. 74.

such extremes of composition. There is no promising method of doing so. Another difficulty presents itself in the very rapid changes from one type to another. Even granting some method of obtaining a heterogeneous liquid, one encounters the problem of maintaining these sharp contrasts in adjacent liquids, for diffusion, though unquestionably a slow process, would nevertheless accomplish much through moderate distances in the time required for the cooling of such masses. On the other hand, it seems reasonably possible both to obtain and to maintain almost any degree of heterogeneity as a result of the accumulation of crystals. On this assumption it is necessary to imagine the source of the olivine-rich types in a portion of the magma reservoir where olivine crystals had accumulated and of the feldspar-rich types where feldspar crystals had accumulated. These partly crystalline masses were thrust into the position where found. The greater the approach to monomineralic composition, the less liquid there could have been. In accordance with this conception it is found that in the allivalite the feldspar crystals are arranged with their elongation in the direction of flow of the sheets, and that this becomes more marked the richer the rock is in feldspar. In the case of bands consisting almost entirely of one mineral, which should have had very little liquid to lubricate their flow, it is found that characters consequent upon this are developed. Thus the nearly pure feldspar rock is described by Harker as strongly fissile and the pure olivine rock as foliated.[1] Possibly connected with the nearly solid condition of these rocks as injected is the fact that their intrusion apparently involved overthrusting, at least it is intimately connected with a line of overthrusting along which earlier, later, and possibly contemporaneous movements took place.

In correspondence with the unusual conditions of formation and intrusion of these ultra-basic rocks we find them to be scarcely duplicated elsewhere. The Russian ultra-basic rocks described by Duparc and Pearce seem to be their nearest relatives. They show a not dissimilar banding of closely related types and possibly may be explained in a like manner. The peridotite dikes are described as

[1] *Op. cit.*, pp. 72 and 87.

"parfois légèrement schisteux."[1] It may be noted at this point, also, that an augitite associated with the perfectly massive alkaline types of the Ice River district, British Columbia, is described as having a "suggestion of a schistose texture."[2] Observations such as these, though seemingly unimportant, may nevertheless have considerable importance in connection with the movement of a mass with very little interstitial liquid. It may well be, also, that in the movement of a mass with a small amount of interstitial liquid lies the secret of the formation of some monomineralic masses of extreme purity. Such movement when it caused a crushing of crystals at their points of contact would necessarily imply a flowing away of some liquid. Continuance of this action might, under certain conditions, result in a squeezing out of the interstitial liquid as from a sponge.

Rocks made up almost exclusively of albite or oligoclase are known, but there is usually evidence, if only of a collateral nature, that solutions have played a prominent part in their formation. Though often occurring as dikes there is never any reason for believing that these materials have ever been molten as such. And so it is with many masses of magnetite, indeed it is not impossible that practically any mineral might occur as dikes having a similar character and origin. Such an occurrence need not, however, affect one's belief that, as a rule, monomineralic rocks are crystal accumulations analogous to the great anorthosite masses and having the characteristics corresponding thereto.

It will be noted that nowhere in the foregoing discussion has an appeal been made to the remelting of the masses of crystals once accumulated. While the writer would not go the length of stating that such action never takes place, he would nevertheless consider that it must be of very exceptional occurrence. It has been shown that the monomineralic rocks are best explained without the aid of the doctrine of remelting, and many of the broader generalizations of igneous geology are opposed to it. For example, the parallelism between sequence of intrusion and sequence of con-

[1] "L'Oural du nord I," *Mem. soc. phys. et d'hist. nat. de Genève*, XXXIV (1902), Fasc. 2, p. 101.

[2] Warren, Allan, and Conner, *Am. Jour. Sci.* (4), XLIII (1917), 75.

solidation is altogether too close to permit one to consider remelting an important factor. Remelting would almost certainly destroy all law and order in this matter. Harker has recently expressed a belief to the contrary, pointing out that the remelting of a solidified mass with basic material at the bottom and acid at the top might take place from the bottom upward.[1] Possibly it might, and in an undisturbed crust it would realize the common sequence of intrusion, but in an earth's crust subject to faulting, folding, and overthrusting it may be doubted whether any regularity would be observed. Disturbance of the stratified mass would often put some of the basic material on a level with or even on a higher horizon than some of the acid material. The remelting of such a disturbed mass would not give rise to any significant regularity in the intrusive sequence.

A CONSIDERATION OF THE CRITERIA FOR THE RECOGNITION OF ONCE MOLTEN ROCKS

If we pass in review the development of ideas concerning igneous or once molten rocks we find them first clearly recognized in surface lavas. It was natural that it should be so, for here we have rocks that, judging from their relations to their surroundings, have evidently flowed as a liquid, and that are being duplicated in flows from active volcanoes at the present day. Then we find a few coming to believe that other rocks, usually quite distinct in appearance and occurring as deep-seated masses only bared by erosion, really are made up of the same material, the difference in appearance being principally due to the difference of conditions under which solidification took place. After much controversy this belief gains general acceptance, especially as a result of the accumulation of facts proving the essential identity of these deep-seated masses with volcanic flows. Originally, then, it was this correspondence of plutonic rocks with volcanic rocks that gave geologists the right to consider them once molten or igneous rocks. Simultaneously with the development of this view numerous facts corroborative of it accumulated, important among these being the manner in which the plutonic masses sent tongues into the surrounding rocks, and

[1] *Journal of Geology*, XXIV (1916), 556.

the light which the microscope threw on the process of crystallization of their mineral constituents, which evidently took place precisely as it should if they were once molten. Eventually, these corroborative facts came to be the criteria for the recognition of an igneous or once molten rock and, at present, in actual practice it is almost exclusively on the basis of the microscopic structure that a rock is placed as igneous or not. Thus judged, the monomineralic rocks are unquestionably to be considered as once molten, but if we revert to the original criteria we find that in some respects they fail to qualify. In the matter of sending tongues into surrounding rocks we find them scarcely typical, and as far as occurrences as lavas are concerned we find them wholly wanting. This apparent discrepancy is due to the fact that we have not made our distinctions fine enough. These rocks were formerly molten, but they were never molten as such. When molten they were part of a complex solution. Monomineralic rocks therefore afford the strongest justification for believing that crystallization controls differentiation. If differentiation took place in magmas wholly liquid, it would seem that all plutonic rocks should have their effusive equivalents. An examination of any table of classification of igneous rocks on a mineralogic basis shows, however, a decisive tendency for plutonic rocks to vary more widely than do effusives, especially among basic rocks, and especially in this matter of running to marked richness in one mineral. This fact would have little significance if it were a fairly common feature of plutonic rocks to lack an effusive equivalent, but it becomes of the greatest significance in connection with the manner of origin here advocated for the monomineralic rocks when it is realized that in this respect the monomineralic rocks stand alone.

VOLUME AND AGE RELATIONS OF MONOMINERALIC ROCKS

Of the monomineralic rocks anorthosite is the only one that occurs in any great amount. The actual volume of pyroxenite and peridotite exposed at the surface of the earth appears to be insignificant.[1] On account of the exceptional period required for the

[1] Daly's figures would indicate the order of magnitude (*Igneous Rocks and Their Origin*, p. 44).

sorting of plagioclase crystals anorthosite can form only from very large masses of magma that cool with great slowness, or if from masses of more moderate size these must be deep-seated. The anorthosite of the large masses normally belongs below the granitic zone so that, whether formed in very large bodies or in bodies of more moderate size, it is an especially deep-seated rock. Peridotites and pyroxenites by reason of the relative ease of sorting of these heavy minerals can form from moderate masses and at moderate depths, and are therefore of widespread occurrence and of general distribution in the geologic column though never exposed in large masses. Anorthosites, on the other hand, being essentially deep-seated are exposed only in terranes that have suffered, locally at least, exceptionally deep erosion, the pre-Cambrian and perhaps early Paleozoic. According to the writer's opinion there are probably large masses of peridotite and pyroxenite, but these have not been exposed at all for the same reason that anorthosite is exposed only in the older terranes. These peridotites and pyroxenites are, as it were, the complements of the granites, which in virtue of their low density are so abundantly exposed. Many will, no doubt, consider the opinion that there are large unexpected masses of pyroxenite and peridotite a pure assumption, and it is quite true that some assumption must be involved in the formation of opinion concerning inaccessible portions of the earth. Nevertheless, an assumption based on analogy with many completely accessible bodies showing density stratification should surely be given a preference over an assumption, tacit or otherwise, that the kind of rocks exposed in any body extend downward indefinitely, which is based merely on lack of evidence, one way or the other, for that particular body. However this may be, it is certain that anyone who believes that anorthosite is a differentiate of gabbroid magma, as most petrologists do, must believe that there is an equivalent amount of pyroxenite somewhere, and if not exposed then presumably in inaccessible regions. At this point the hypothesis of crystal accumulation steps in with a rational explanation of the not infrequent lack of pyroxenite in anorthosite terranes, very difficult to account for on the doctrine of liquid differentiation. Being an accumulated mass of crystals, pyroxenites usually remain sub-

stantially where formed. If liquid they could not fail to be represented very prominently in all anorthosite terranes, for the liquid would be freely intruded into overlying rocks at every disturbance experienced by them.

SUMMARY

Anorthosites are made up almost exclusively of the single mineral plagioclase, and in virtue of this fact they present a very special problem in petrogenesis. The conception of the mutal solution of minerals in the magma and the lowering of melting temperature consequent thereon is no longer applicable. Yet anorthosites give no evidence of being abnormal in the matter of the temperature to which they have been raised, in other words, they give no evidence of having been raised to the temperature requisite to melt plagioclase. A possible alternative is that they may never have been molten as such, and are formed simply by the collection of crystals from a complex melt, probably gabbroic magma. This possibility is in harmony with the expectations that grow out of experimental studies and for this reason a consideration of the likelihood that anorthosites have originated in the stated manner becomes imperative.

A consideration of the method whereby accumulation of plagioclase crystals might take place leads to the conclusion that the most promising is the separation by gravity of the femic constituents from gabbroid magma, while the plagioclase crystals, which are basic bytownite, remain practically suspended. Then, at a later stage, when the liquid has become distinctly lighter, having attained diorite-syenite composition, the plagioclase crystals, which are now labradorite, accumulate by sinking and give masses of anorthosite, at the same time leaving the liquid out of which they settle of a syenitic or granitic composition.

Some of the consequences of this manner of origin of anorthosite are as follows. Typical anorthosite, very poor in bisilicates, should not occur as small dikes, for a mass of accumulated crystals should have little invading power. A proportion of about 15 or 20 per cent bisilicates or other foreign material such as orthoclase and quartz should be necessary for the formation of small dikes. Typical anorthosite should for like reasons not occur as an effusive

rock, a rather large proportion of minerals other than plagioclase being necessary before such an occurrence would become possible. Anorthosite should be intimately associated with gabbro, but perhaps as intimately with syenite or granite. Anorthosites should commonly be labradorite rocks rather than bytownite or anorthite rocks.

A consideration of anorthosites with special reference to the Adirondack and Morin areas gives some reason for believing that anorthosites do show the requisite characters. For the Adirondack area especially, evidence is adduced favoring the possibility that there anorthosite and syenite may still occupy the relative positions in which they were generated by the process outlined, the Adirondack complex being interpreted as a sheetlike mass with syenite above and anorthosite below.

Other monomineralic rocks present essentially the same problem and are restricted in their occurrence in substantially the same manner if we consider especially those that approach most closely to the strictly one-mineral character. All of the monomineralic rocks do occur, however, as dikes and dikelike masses in essentially contemporaneous, congeneric, igneous rocks, a fact that may be interpreted as due to the intrusion of a heterogeneous, partly crystalline mass.

On the whole the inquiry gives considerable support to the belief that the monomineralic rocks, of which the anorthosites are perhaps the most important representatives, are generated by the process of collection of crystals under the action of gravity.

THE MIDDLE PALEOZOIC STRATIGRAPHY OF THE CENTRAL ROCKY MOUNTAIN REGION

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PART II

STRATIGRAPHY—*Continued*

UPPER CAMBRIAN AND EARLY ORDOVICIAN

Members o and 1.—Throughout western Wyoming, and at least as far north as Livingston, Montana, the thin-bedded upper part of the Gallatin formation rests upon a very massive cliff-making dolomite (Member 1), ranging up to 400 feet or more in thickness. Near Three Forks this member constitutes the "mottled limestone" (middle division of the Gallatin formation) of Peale,[1] which was correlated by Weed[2] with the Pilgrim limestone of the Little Belt Mountains. It corresponds roughly in position and in general character to the Hasmark formation, which was differentiated by Emmons and Calkins[3] in the Philipsburg quadrangle, Montana, and tentatively correlated by them with the Pilgrim.

Underlying this massive member in Wyoming and Montana is a zone of weaker strata (Member o) in which green shales predominate, interstratified with thin beds of dolomite and flat-pebble limestone conglomerate. This belt includes the "*Obolella* shales" of Peale[4] in the Three Forks quadrangle, and at least the upper part of the Gros Ventre shale of Blackwelder[5] in western Wyoming; and is probably represented in the Park shale of Weed[6] in Montana.

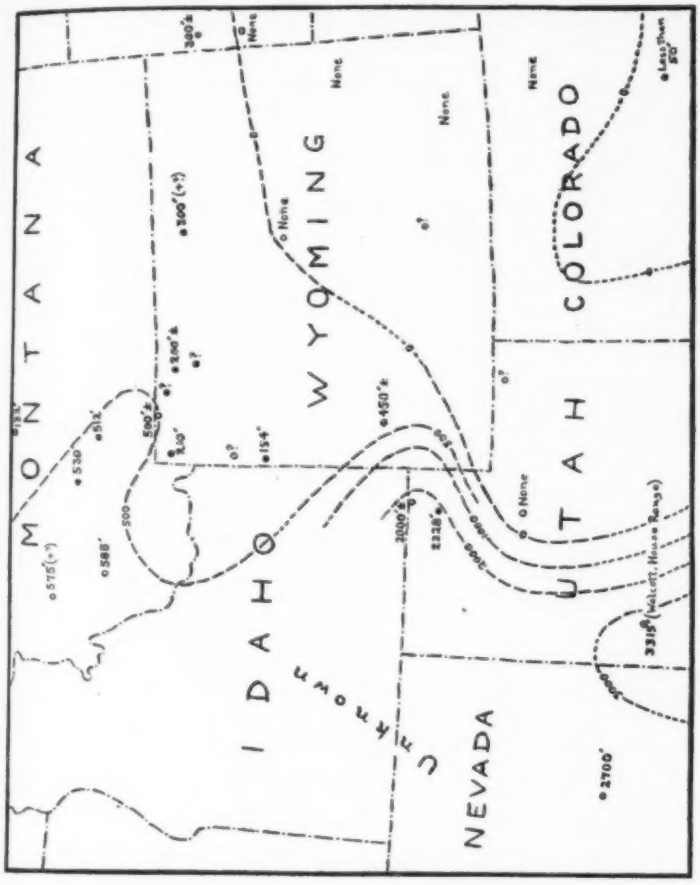
[1] A. C. Peale, "Description of the Three Forks (Montana) Sheet," *Geol. Atlas U.S.*, Folio 24 (1896).

[2] W. H. Weed, "Geology of the Little Belt Mountains, Montana," *U.S. Geol. Survey, 20th Ann. Rept.*, Part 3 (1900), Pl. 40, opp. p. 284; p. 286.

[3] W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *U.S. Geol. Survey, Prof. Paper 78* (1913), pp. 57–59, 63.

[4] *Op. cit.* [5] Eliot Blackwelder, unpublished manuscript. [6] *Op. cit.*, p. 286.

The upper part of the Cambrian sequence in Utah is not unlike that in Wyoming. There is a very prominent massive member (No. 1), which is overlain by thin-bedded dolomites (Members


MONTANA
WYOMING
COLORADO
UTAH
IDAHO
NEVADA
UTAH
None
None
None

flat-pebble conglomerate. Walcott[1] places the lower boundary of the Upper Cambrian approximately in the middle of this lower series (Member o), at the base of a sandstone member. No fossils have been found in the 1,000 feet of beds (Nounan formation) next beneath that horizon, but the Bloomington formation, next below, carries a Middle Cambrian fauna.[2] As the shales of Member o in Montana and Wyoming have been assigned to the Middle Cambrian, they are possibly to be correlated with the green shales of the Bloomington formation.

Members 3 and 4 in northern Utah.—The main flat-pebble conglomerate series (Member 3) on Blacksmith Fork is 800 feet thick, and has yielded fossils at several horizons. These collections have established the Ordovician age of all but the lower 190 feet of the member, which is left by Walcott[3] in the Upper Cambrian. The Garden City formation in the Randolph quadrangle is described by Richardson[4] as containing flat-pebble conglomerate throughout its estimated 1,000 feet of thickness, but it may include a representative of Member 4 as well as of Member 3. Richardson's collections[5] are like those of the writer from Member 4 on Blacksmith Fork, and clearly indicate that this formation is of Beekmantown age, possibly ranging up into slightly later time.

Richardson[6] states that he has evidence of an unconformity between Cambrian and Ordovician, but this evidence is not yet published. Elsewhere in Utah no evidence has been cited of an interruption in sedimentation at this horizon, and it is certain, as indicated by the exact similarity between the latest Cambrian and the earliest Ordovician rocks, that if similar conditions were not continuous from the former period into the latter in this region they returned with very little modification after the interruption. The upper record succeeds the lower without the intervention of any clastic sediments.

[1] C. D. Walcott, "Cambrian Cordilleran Sections," *Smithsonian Misc. Coll.*, LIII (1910), 193.

[2] Walcott, *op. cit.*, pp. 194–95. [3] *Op. cit.*, p. 191.

[4] G. B. Richardson, "The Paleozoic Section in Northern Utah," *Amer. Jour. Sci.*, 4th Ser., XXXVI (1913), 406–15.

[5] *Op. cit.*, pp. 408–9. [6] *Op. cit.*, p. 408.

Correlation with the Pogonip group of Nevada.—The Pogonip group of the Eureka district of Nevada, called Lower Silurian by Hague[1] and Walcott,[2] probably includes equivalents of the Garden City formation and part or all of the St. Charles formation (Upper Cambrian, Blacksmith Fork). The upper part of the Pogonip group carries a fauna, considered by Walcott[3] to be of Chazyan age, which bears a notable resemblance to the faunas of the Garden City formation.

Member 3 in Wyoming and Montana.—In Wyoming the thin-bedded Upper Cambrian–Lower Ordovician(?) sequence, including flat-pebble conglomerate, is nowhere represented by more than 500 feet of strata, but its characters are typical of Member 3 wherever it is exposed. In southwestern Montana it forms the highest member of the Gallatin formation.

The faunas so far collected from this sequence in both Wyoming and Montana are very meager, a fact which has made its correlation a subject of dispute in various localities. In the Bighorn Range, Member 3 constitutes the uppermost part of the Deadwood formation, which is called by Darton[4] Middle Cambrian; but the only species Darton names as coming from the upper 600 feet of the formation (about 1,000 feet thick in all) is *Dicellomus politus*, which is associated in one locality[5] with fragments of a trilobite resembling *Ptychoparia oweni*. Some collections from the upper part of the Gallatin formation in western Wyoming, comprising three species of *Eoorthis* and some fragmentary trilobite remains, have been referred to the Upper Cambrian by paleontologists of the United States Geological Survey.[6] Member 3 probably is represented

[1] Arnold Hague, "Geology of the Eureka District, Nevada," *U.S. Geol. Survey, Monographs*, XX (1892).

[2] C. D. Walcott, "Paleontology of the Eureka District," *U.S. Geol. Survey, Monographs*, VIII (1884).

[3] *Op. cit.*, pp. 3–4.

[4] N. H. Darton, "Geology of the Bighorn Mountains," *U.S. Geol. Survey, Prof. Paper 51* (1906), p. 26.

[5] N. H. Darton, "Fish Remains in Ordovician Rocks in the Bighorn Mountains, Wyoming, with a Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 551.

[6] Eliot Blackwelder, personal note. Cf. C. D. Walcott, "Cambrian Brachiopoda," *U.S. Geol. Survey, Monographs*, XXXI (1912), 233, Lot 302*e*.

in the Red Lion formation (250 feet thick) of the Philipsburg quadrangle, Montana, from which Kindle[1] has made some collections identified by Walcott[2] as Upper Cambrian.

The beds in question probably are equivalent to some part or parts of Member 3 of the Utah sequence, and it is therefore possible that they may include strata of Lower Ordovician age.

The Maxfield formation of the central Wasatch.—Hintze[3] has described a sequence of 481 feet of limestones and shales "disconformably overlying the Alta shale"[4] on the South Fork of Big Cottonwood Canyon, southeast of Salt Lake City, which he has named the Maxfield formation, and has tentatively assigned to the Ordovician. The Alta shale (150–200 feet thick), which rests on the basal Cambrian quartzite, carries a Lower Cambrian fauna near its base and a Middle Cambrian fauna at a higher horizon.[5] Disconformably above the Maxfield lies the Devonian Benson limestone.

No fossils have been found in the Maxfield formation. Its reference to the Ordovician was suggested by the "wormy" appearance of the chief limestone members of the formation, which Hintze likened to the Lowville ("Birdseye") limestone of New York, and by the occurrence at the top of the formation of 10 feet of shale alternating with typical flat-pebble ("edgewise") limestone conglomerate, which Hintze[6] noted had been described from Lower Ordovician strata elsewhere. Unfortunately for this correlation, conglomerate of that type is abundantly developed in northern Utah, not only in the Garden City (Beekmantown) formation, but in the St. Charles (Upper Cambrian) and Bloomington (Middle Cambrian) formations. The "wormy" appearance is to be seen in various members of each and all of the six Middle and Upper

[1] E. M. Kindle, "Fauna and Stratigraphy of the Jefferson Limestone in the Northern Rocky Mountain Region," *Bull. Amer. Pal.*, No. 20, 1908, pp. 10–11; also Emmons and Calkins, *op. cit.*, p. 63.

[2] C. D. Walcott, *op. cit. ult.*, p. 233, Lots 302*q*, 302*r*.

[3] F. F. Hintze, Jr., "A Contribution to the Geology of the Wasatch Mountains, Utah," *Annals New York Acad. Sci.*, XXIII (1913), 85–143.

[4] *Ibid.*, p. 105.

[5] C. D. Walcott, *U.S. Geol. Survey, Bull. No. 81*, 1891, p. 319.

[6] *Op. cit.*, p. 106.

Cambrian formations at Blacksmith Fork, but has not been noted in the Garden City formation. Amounts of shale comparable to that in the Maxfield (about 180 feet, all told) are present only in the Langston, Ute, and Bloomington formations at Blacksmith Fork.

Furthermore, flat-pebble conglomerate is abundant throughout the lower 600 feet (about half) of the Garden City formation at Blacksmith Fork, but has not been noted in the upper half of the formation there at all. The relation noted in the Maxfield formation, of 480 feet of interbedded shales and limestones with flat-pebble limestone conglomerate in the upper 10 feet only, could thus not be matched in the Garden City formation. A sequence almost precisely similar to that of the Maxfield formation does occur, however, in the Bloomington formation.

The Maxfield formation of the central Wasatch, therefore, is probably of Cambrian age, and bears a striking likeness to the Middle Cambrian Bloomington formation of the Bear River plateau, 75 miles farther north.

The close relation of the Canadian series to the Upper Cambrian series.—If the upper limit of the Cambrian system in northern Utah has been defined correctly, the changes which took place between Canadian (or Chazyan) and Trenton time in the Rocky Mountain–Great Basin paleogeographic province were more notable than those which occurred between Upper Cambrian and Canadian time in that region. The latest sediments assigned to the Upper Cambrian are of the same type as the Canadian deposits, whereas the sediments of Trenton age are very different from either of the former. The erosion preceding the beginning of Trenton sedimentation is known to have been extensive, whereas evidence of erosion between Upper Cambrian and Canadian time is reported from only one locality.

The physical evidence thus goes to show that the affinities of the Western Canadian are rather with the Cambrian than with the higher Ordovician.

Is the Ozarkian system represented here?—If the Ozarkian period of Ulrich is represented in the western province, it must be by some part of the Upper Cambrian–Lower Ordovician sequence above

described. In the absence of an adequate description of the fauna of the typical Ozarkian, it is difficult to make comparison therewith. The base of the Ordovician was placed by Walcott[1] at Blacksmith Fork at the first appearance of cephalopods. As determined by Richardson[2] in the Randolph quadrangle, the base of the Garden City formation there is marked by the appearance of several genera of coiled gastropods. The post-Cambrian, pre-Swan Peak (see below) series thus defined has a thickness on Blacksmith Fork of 1,272 feet, which is 68 per cent greater than the total thickness of the overlying Ordovician, including the Richmond. As above noted, Richardson describes a marked unconformity at the top of the Cambrian in the Randolph area. These faunal distinctions and this physical evidence may warrant the recognition of the series in question as a separate system; but there is no evidence yet at hand to suggest its subdivision into *two* systems, Ozarkian and Canadian. It is possible that the St. Charles formation includes a representative of the former.

Up to the present, however, the Ozarkian has not been recognized in the Rocky Mountains.

THE ORDOVICIAN QUARTZITES AND SANDSTONES

The Eureka and Swan Peak quartzite.—In eastern Nevada the unfossiliferous Eureka quartzite, ranging from 200 to 500 feet in thickness, lies in apparent conformity upon the Pogonip limestone. The upper surface of the Eureka quartzite is clearly an irregular erosion surface. It is overlain by the Lone Mountain limestone, which carries a Trenton fauna near its base.[3]

The Eureka quartzite corresponds closely in stratigraphic relations to the quartzite at Geneva[4] and to the Swan Peak[5] quartzite, both in northern Utah, which attain a similar thickness. Unconformity is evident above the Swan Peak quartzite in the Randolph quadrangle,[6] and farther south the post-Swan Peak erosion locally

[1] C. D. Walcott, "Cambrian Cordilleran Sections," *Smithsonian Misc. Coll.*, LIII (1910), 191.

[2] *Op. cit.*, pp. 408–9. [3] Hague, *op. cit.*, pp. 58–59.

[4] Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, XXI (1910), 526–27.

[5] Richardson, *op. cit.*, p. 408. [6] *Ibid.*

resulted in the complete removal of the quartzite, so that in the section exposed on Blacksmith Fork the succeeding dolomites of Trenton(?) age rest unconformably on the Garden City formation.

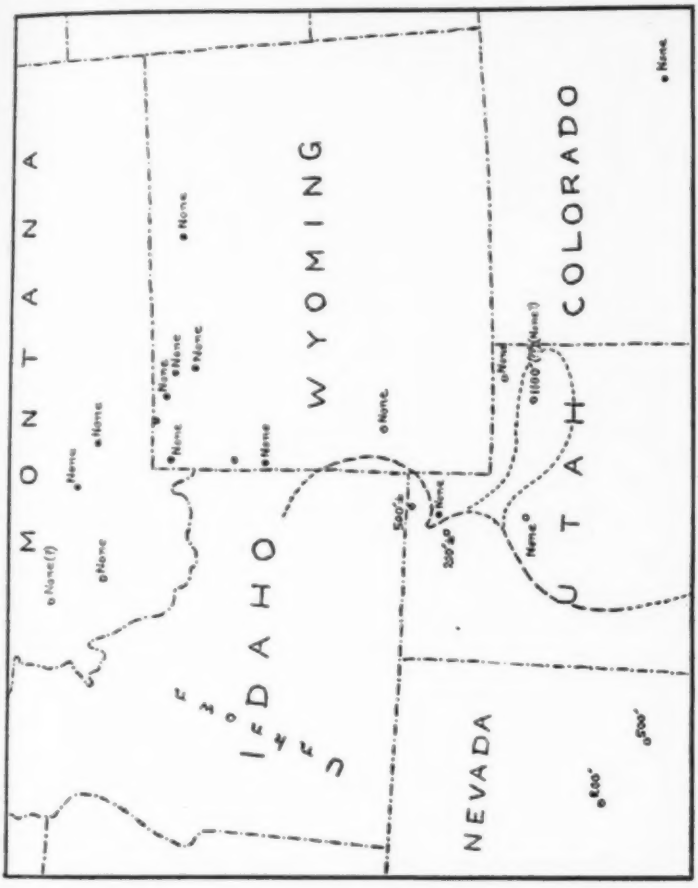


FIG. 7.—Map showing the extent and thickness of the Chazyan (?) quartzites

The Swan Peak quartzite contains a small fauna which has been referred tentatively to the Chazyan by Ulrich.[1] Four of the eight forms identified from the Swan Peak are found also in the similarly

[1] *Op. cit.*, p. 408.

meager fauna of the quartzite at Geneva.[1] There is no representative of these quartzites in the section described by Hintze[2] in Salt Lake County, Utah, 75 miles south of Blacksmith Fork.

The absence of the Swan Peak quartzite from the Blacksmith Fork section is especially notable in view of the fact that it occurs with a thickness of several hundred feet less than 20 miles to the northeast, in the Randolph area, and also less than 20 miles away in the opposite direction, near Geneva.

The "Ogden quartzite" in the Uinta Range.—In the south slope of the Uinta Range a quartzite attaining a maximum thickness of about 1,100 feet lies between the Mississippian system and the barren Lodore shales (Cambrian?). Weeks[3] correlated this formation with that which is called in this paper the Swan Peak quartzite, in the region east of Cache Valley, Utah; and he applied to both formations the same name, "Ogden quartzite." As no fossils have been found in the "Ogden quartzite" in the Uinta Range, the correlation rests on an insecure basis.

No representative of this quartzite was noted on the north flank of the Uinta Range.

The sandstone at the base of the Bighorn formation.—The Trenton dolomites in Wyoming for the most part lie directly on the flat-pebble conglomerate series, but locally they are accompanied by a thin basal sandstone carrying a late Black River or early Trenton fauna, including fish remains.[4] This sandstone is correlated with the fish-bearing Harding sandstone of Colorado,[5] which likewise is overlain by dolomites of Trenton age. It is probable, as has usually been considered, that this sandstone member represents an introductory stage of the Trenton submergence rather than that it is a deposit of an earlier submergence, separated by an epoch of erosion from the Trenton proper, as is the case with the Swan Peak and Eureka quartzites. The faunal lists from the Swan

[1] Blackwelder, *loc. cit. uls.* [2] *Op. cit.*

[3] F. B. Weeks, "Stratigraphy and Structure of the Uinta Range," *Bull. Geol. Soc. Amer.*, XVIII (1907), 436–37, 441.

[4] N. H. Darton, *op. cit.* (1905), p. 551; and Bald Mountain–Dayton Folio, Wyoming, *Geol. Atlas U.S.*, Folio No. 141 (1906), p. 4.

[5] N. H. Darton, *op. cit.* (1905), p. 552; and Folio 141, p. 4.

Peak quartzite[1] and the quartzite at Geneva[2] include no species, and only two genera (*Orthis* and *Endoceras*) in common with the published lists of fossils from the Harding sandstone[3] and the basal Bighorn sandstone.[4]

THE MIDDLE AND UPPER ORDOVICIAN DOLOMITES

Extent of the Bighorn dolomite.—The Bighorn dolomite was named by Darton[5] from its characteristic exposures on both flanks of the Bighorn Range in northern Wyoming, and by him was correlated with the Whitewood limestone of the Black Hills and with the Fremont limestone of the Front Range of Colorado.[6] The same author later recognized the Bighorn dolomite in the Owl Creek[7] and Wind River[8] ranges of Wyoming. Fisher[9] briefly described its occurrence in Cedar and Rattlesnake Mountains, west of Cody, Wyoming. Blackwelder[10] has identified it in the Gros Ventre and Teton ranges, farther west.

The Bighorn dolomite in Montana.—Both Darton[11] and Fisher[12] prophesied that the Bighorn dolomite would be found to be included in the "Jefferson limestone" of Hague, and the truth of this

[1] Richardson, *op. cit.*, p. 410. [2] Blackwelder, *op. cit.* (1910), p. 527.

[3] N. H. Darton, "Fish Remains in Ordovician Rocks in the Bighorn Mountains, Wyoming, with a Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 563.

[4] *Ibid.*, pp. 554–56, footnote.

[5] N. H. Darton, "Comparison of the Stratigraphy of the Black Hills, Bighorn Mountains, and Rocky Mountain Front Range," *Bull. Geol. Soc. Amer.*, XV (1904), 379–448.

[6] N. H. Darton, "Description of the Bald Mountain and Dayton Quadrangles," *Geol. Atlas U.S.*, Folio 141 (1906), p. 4.

[7] N. H. Darton, "Geology of the Owl Creek Mountains," Fifty-ninth Congress, 1st session, Senate Document No. 219 (1906), p. 15.

[8] N. H. Darton, "The Paleozoic and Mesozoic of Central Wyoming," *Bull. Geol. Soc. Amer.*, XIX (1908), 403–74.

[9] C. A. Fisher, "Geology and Water Resources of the Bighorn Basin, Wyoming," *U.S. Geol. Survey, Prof. Paper 53* (1908), p. 12.

[10] Eliot Blackwelder, unpublished manuscripts, *U.S. Geol. Survey.*

[11] N. H. Darton, "Fish Remains in Ordovician Rocks in the Bighorn Mountains, Wyoming, with a Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 554.

[12] *Op. cit.*

prophecy has now been demonstrated by the writer's work. The Bighorn dolomite is characteristically developed throughout the length of the Absaroka Range, and has yielded Ordovician fossils

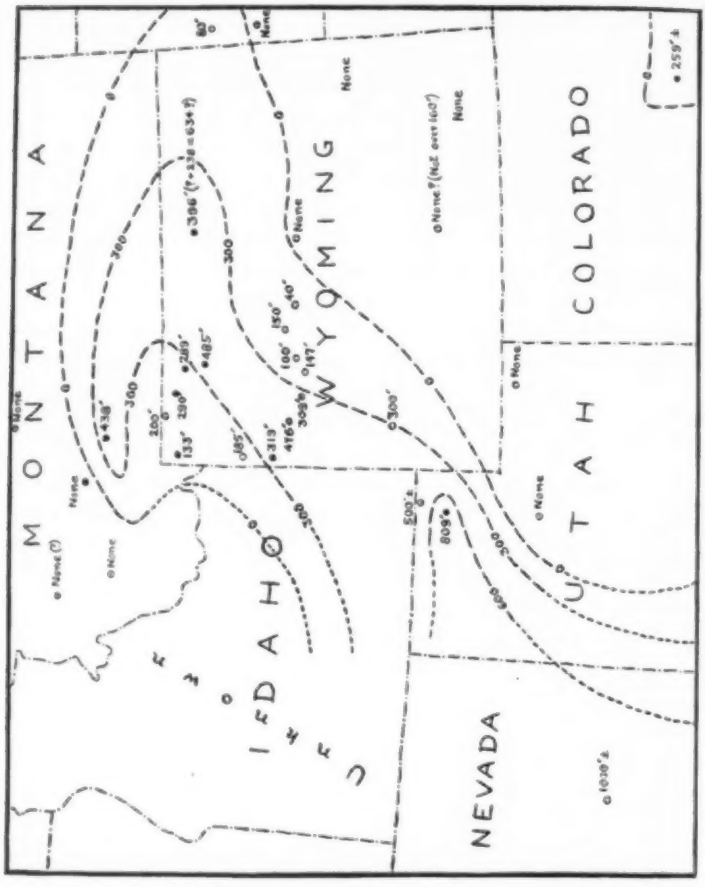


FIG. 3.—Map showing the extent and thickness of the Bighorn dolomite (Middle and Upper Ordovician) and correlated formations.

in the Crandall (Wyoming) and Livingston (Montana) quadrangles. It is a remarkable fact that, although this formation is 438 feet thick in Livingston Peak, it has no known continuation north of that point, nor west beyond the Gallatin Range.

Members 2–4.—There can be little doubt as to the validity of most of the correlations of Trenton strata shown in the preceding table and diagrams, except in Utah and Nevada. The main massive member (No. 4) of the Lower Bighorn, with its accompanying basal weaker strata (Members 2 and 3) and its cap of smooth, nearly chalky, dolomite, constitutes a highly characteristic and almost unique series. Furthermore, Member 2 is fossiliferous, and Member 4 is sparingly so in nearly all localities.

The upper half of the massive member in the Blacksmith Fork section, which the writer has called the Lower Fish Haven dolomite, is similar in all essential respects to the massive Trenton member of the typical Bighorn. It is marked off from the Richmond above by a conglomerate, and disconformity at its base is sufficiently indicated by the absence of the (Chazyan?) quartzite which intervenes at that horizon elsewhere in northern Utah. This lower Fish Haven dolomite carries *Halysites*, which is not known from rocks older than Mohawkian.

The lower part of the Lone Mountain limestone, which unconformably overlies the Eureka quartzite in western Nevada, carries a fauna assigned by Walcott[1] to the Trenton. Ulrich[2] has voiced the opinion that part of the Lone Mountain limestone is older than the Bighorn dolomite; but it is probable that the former formation contains a representative of the Trenton series.

Members 5–7; the Leigh formation.—Members 5–7 of the Middle and Upper Ordovician series constitute a distinct and very widely developed unit. In the Goose Creek Ridge section there is little ground for differentiating these three from each other; but the lowest Richmond fauna occurs in the beds there marked as Member 6. In the Crandall Creek and Dead Indian Creek sections there is a conspicuous surface of disconformity, with a basal breccia, at the base of Member 6. As this is the only disconformity for which physical evidence has so far been noted anywhere within the limits of the Bighorn formation, and as it coincides (by lithologic correla-

[1] Arnold Hague, *op. cit.*, pp. 61–62, 196–97; also appendix by C. D. Walcott, pp. 324–25.

[2] Cf. Bailey Willis, "Index to the Stratigraphy of North America," *U.S. Geol. Survey, Prof. Paper 71* (1912), p. 169.

FIG. 8.—Map showing the extent and thickness of the Bighorn dolomite (Middle and Upper Ordovician) and correlated formations.

tion of beds both above and below) with the base of the known Richmond part of the Bighorn in the type locality, it probably represents the hiatus which was inferred by Darton between the Trenton and Richmond members of the Bighorn.

In the Teton Range, there is likewise an unconformity at the base of Member 6. Blackwelder[1] proposes the recognition of Members 6 and 7 in that region, and of corresponding strata in the Gros Ventre Range, as a distinct formation, to be called the *Leigh*, from its typical development on Leigh Creek, in the Teton Range. In view of the fact that this group of strata, in its type locality, is bounded both above and below by unconformity, and is lithologically quite distinct from the underlying massive member (Member 5 is not present in the Teton River section), its recognition as a separate formation seems justified. In the Absaroka Range the corresponding beds differ little in character from the upper part of the Trenton series (Member 5), but are marked off from it by unconformity, as just described.

Between Members 4 and 8 of the Livingston Peak section, light-colored dolomites of the Leigh type occur interbedded with darker, gray-brown, more coarsely crystalline dolomites. In the Blacksmith Fork section there is an interbedding of light and dark strata through a thickness of 130 feet above the conglomeratic horizon, which is taken as the probable base of the Richmond series. Above this sequence there is an 8-foot stratum corresponding closely to the typical Leigh in character, and directly underlying the main massive part of the Fish Haven, which is correlated with Member 8. The first sediments deposited after the pre-Richmond emergence seem to be more variable in character from place to place than are the strata above them, or the members of the Trenton series.

Members 8 and 9.—Member 8 is in some places, in lithologic characters, essentially similar to Member 4, but is in no case quite so thick as the latter. On Goose Creek Ridge there are only two 12-foot massive beds of this type, themselves separated by 20 feet of less resistant dolomites, between the typical Leigh (Members 6 and 7) below and the main fossiliferous, thin-bedded part of the

[1] Eliot Blackwelder, personal note.

Richmond series above. It is possible that the much thicker massive dolomite characterizing the Upper Bighorn in the Absaroka Range is equivalent to a part of this thin-bedded series (called Member 9), as well as to the underlying more massive beds. On Blacksmith Fork, Member 8 forms the main body of the Upper Fish Haven dolomite. In common with several other parts of the Ordovician system, it is somewhat darker in color there than in Wyoming.

The highly fossiliferous, thin-bedded dolomites (Member 9) of the Upper Bighorn in the Bighorn Range unfortunately are not typically developed elsewhere.

There is no representative of the Bighorn in Hintze's[1] section in the central Wasatch, nor in the Uinta Range.[2]

[1] F. F. Hintze, Jr., *op. cit.* [2] F. B. Weeks, *op. cit.*

A FEW INTERESTING PHENOMENA ON THE ERUPTION OF USU

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The eruptions of Japanese volcanoes for the past fifty years have been almost invariably of the Strombolian type. But recently there have been displayed five different types which may be listed as follows: (1) an appearance of a new volcanic island,[1] (2) a new lava dome in the crater of Tarumai, (3) 45 craterlets on the slope of Mount Usu, (4) ejecting lava up in the craters of Asama[2] and Mihara,[3] and (5) lava flows on Sakurajima. Partial descriptions of the Tarumai and Usu have been published by the writer,[4] while an account by Professor B. Koto of the third will appear in the near future.

In the southern part of Hokkaido, in North Japan, three volcanic eruptions took place between 1905 and 1910. Komagatake was in eruption in August, 1905, Tarumai in April, 1909, and Usu in July, 1910. A line connecting these three volcanoes lies in a northeast to southwest direction and represents the northern extremity of the Nasu volcanic chain. The three volcanoes mentioned are about equally distant from each other (48 km.). The explosion of Komagatake was simple and on a small scale, ejecting fragments around the crater and ashes around the foot of the volcano for a few days only, while that of the Tarumai[5] was more

[1] T. Wakimidzut, "Report on the Ephemeral Volcanic Island in the Iwojima Group," *Bulletin of the Imperial Earthquake Investigation Committee*, No. 56 (1907).

[2] F. Omori, *Bulletin of the Imperial Earthquake Investigation Committee*, VI, No. 1 (1912).

[3] Y. Okamura, *Bulletin of the Imperial Geological Survey of Japan*, No. 48 (1914).

[4] *Report of the Imperial Earthquake Investigation Committee*, No. 64 (1909). Official Report of Hokkaido Colonization (1910).

[5] Y. Ōinouye: *Report of the Imperial Earthquake Investigation Committee*, No. 64 (1911); H. Shimotomai, *Zeitschrift der Gesellschaft für Erdkunde zu Berlin*, No. 9 (1912).

severe. The Usu eruption is the latest one among the three, which was quite similar to that on Etna in September, 1911. This volcano is located between the other two, in longitude E. 140° 49′ 30″ and latitude N. 42° 33′, and lies between "Volcano Bay" on the south and Lake Toya (80 m. higher than sea-level) on the north. Usu is a low, conical, active volcano, 736 m. above the sea, and has a crater 2 km. in diameter, within which there are

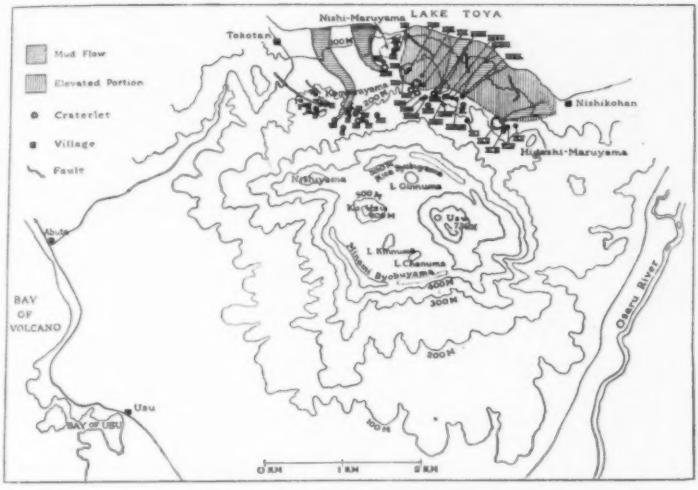

FIG. 1.—Map of Volcano Usu, showing craterlets on the northern slope

two domes occupying respectively the east and the west end of the crater (Fig. 1). The eastern of these domes, O-usu (736 m. AT), looks new, while the western one, Ko-usu (609 m. AT), appears much older. Ko-usu has a few small, steaming pits on the top of its dome, while O-usu has one only on the west side of its dome. The topography, geology, and history of Usu have been well described by Professors F. Omori[1] and D. Sato.[2] Hence only the especially interesting details of the eruptions will be discussed here.

[1] *Bulletin of the Imperial Earthquake Investigation Committee*, V, No. 1 (1911).

[2] *Bulletin of the Imperial Geological Survey of Japan*, XXIII, No. 1 (1913).

I. EARTHQUAKES AND ROARINGS

Preceding the eruption there were frequent earthquakes, seeming to repeat the past history of the mountain, which has always exhibited the "foreshocks" in advance of an eruption. But the writer believes that the occurrence of so many earthquakes in the neighborhood of a volcano within the limits of Japan is a rare phenomenon. It was rumored that slight earth movements were

FIG. 2.—A fissure on the road near Abuta

noticed six days before the eruption. But, as observed by a few persons, the first earthquake began on the evening of July 21, four days in advance of the eruption, and successive earth tremblings were felt from the morning of July 22, continuing through the eruption and for two months thereafter. Numbers of these quakes were felt at Nishimombetsu, 8.4 km. southeast of Usu, 25 on July 22, 110 on July 23, 354 on July 24, 163 on July 25, and thereafter in gradually decreasing numbers. It was on the evening of July 25 that the first eruption took place, and, after it had relieved the strains to some extent, the quakes began to decrease in number.

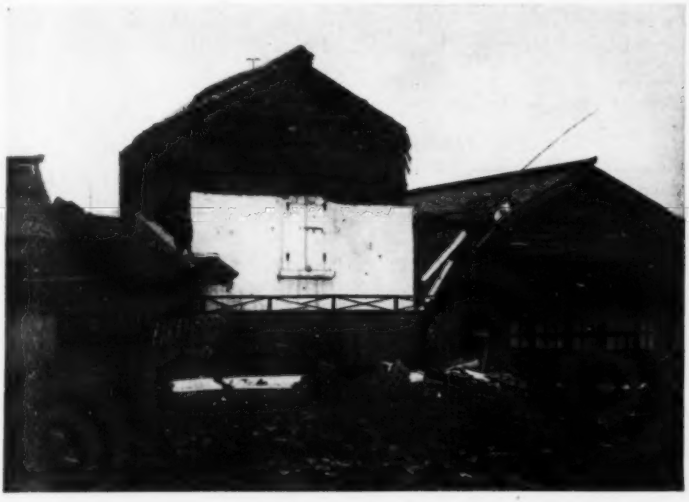

FIG. 3.—A house destroyed by the severe earthquake at 4:30 P.M. on July 24, 1910

FIG. 4.—A monument shaken down by the severe earthquake at 4:30 P.M. on July 24, 1910.

The report of the Municipal Office and the members of the Meteorological Observatory of Sapporo and Hakodate give the numbers in Table I.

TABLE I

NUMBER OF EARTHQUAKES OBSERVED AT NISHIMOMBETSU

Date	Violent	Strong	Weak	Tremor	Total
July 22	.....	.....	13	12	25
23	.....	8	48	54	110
24	1	28	134	150	313+40.5*
25	1	19	58	85	163
26	.....	1	11	16	28
27	.....	3	14	5	22
28	.....	6	3	8	17
29	.....	1	2	9	12
30	.....	1	3	1	5
31	.....	.....	2	1	3
August 1	.....	.....	2	4	6
2	.....	.....	.....	2	2

* Lack of observation for three hours. The number is estimated by means of an average for the three preceding and the three following hours.

From hourly observations the following results were obtained.

From July 22, 7:00 A.M., to July 23, 7:00 P.M., 36 hrs., 66 quakes, 1.8 per hr.
From July 23, 7:00 P.M., to July 25, 8:00 A.M., 37 hrs., 533 quakes, 14.4 per hr.
From July 25, 8:00 A.M., to July 25, 10:00 P.M., 14 hrs., 48 quakes, 3.4 per hr.

The writer's visit to Mount Usu was made on the afternoon of July 24, amid the climax of the quaking. At that time the quakes occurred rather oftener than once in five minutes. The houses trembled so from the subterranean violence that the windows rattled continually throughout the entire day, and made so much noise that no one could stay within the houses. It was noticed that every quake was preceded by the sound which seemed to come from deep within the earth, or as if heavy artillery were being fired in the distance. But sometimes on the east side of the mountain, or in the direction of Volcano Bay, probably owing to the echoes, the same sound was heard. It frequently happened that the sound was first heard in the distance; then a landslide was seen on the dome of O-usu; and following almost immediately the quivering of the earth was felt. A year previous, when the writer visited Usu, a small column of steam was seen to rise from the small pit on the west side of O-usu, and this was the same in

FIG. 5.—The largest mud cone at Usu village. Taken July 30, 1910

FIG. 6.—Numerous mud cones in the Bay of Usu. Taken July 30, 1910

FIG. 7.—A fault of 1 m. throw, at the west foot of the Kompirayama. Taken August 2, 1910.

FIG. 8.—The same fault which has increased its throw to 2 m. Taken September 4, 1910.

amount when the second visit was made during the time of the eruption under discussion. The surrounding country was noted

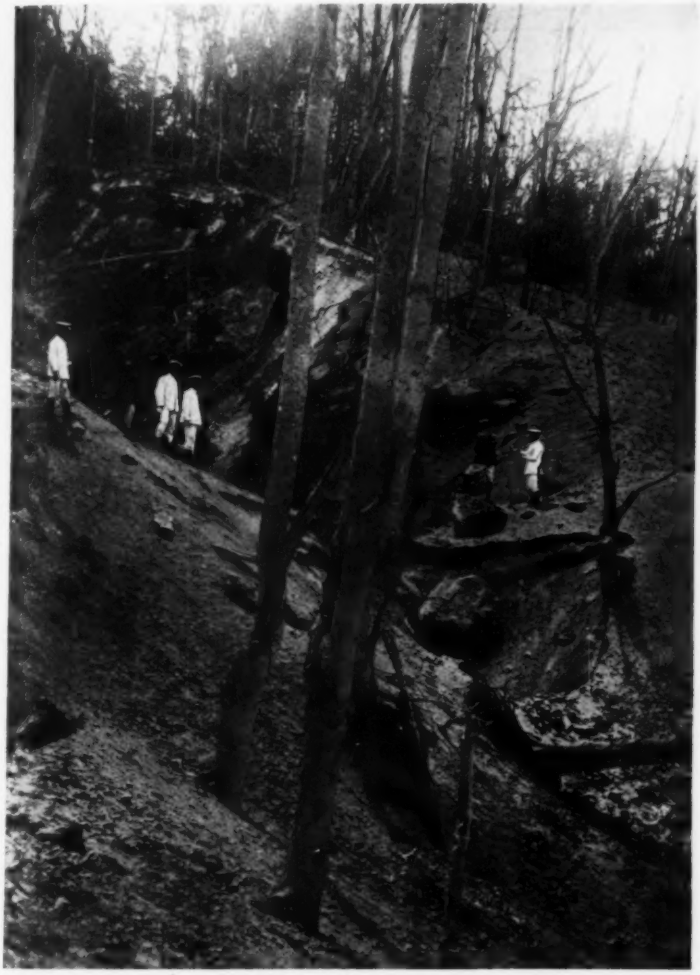

FIG. 9.—The first explosion crater on the Kompirayama. Taken July 26, 1910

to be the same topographically as it had been on the previous visit. Judging from the history of this volcano, the writer recognized

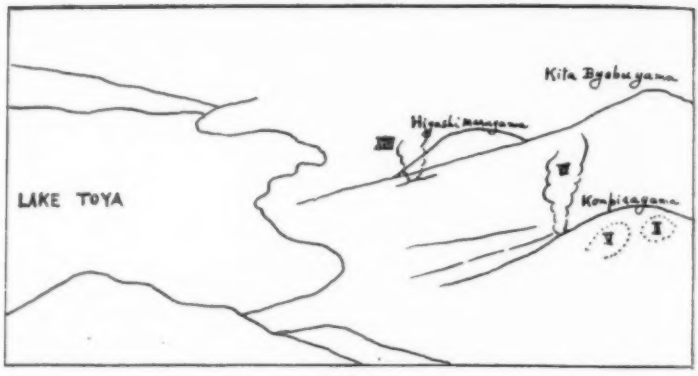

FIG. 10a.—A sketch of craters from the west. 5:00 P.M., July 27, 1910
FIG. 10b.—A sketch of craters from the northwest. 11:20 P.M., July 28, 1910
FIG. 10c.—A sketch of craters from the north. 6:00 P.M., July 29, 1910

that the preliminary warnings were the symptoms of an eruption, and, watching the crater every moment during the day and night and the following day, he observed in detail the phenomena. The number of earthquakes, as well as their vigor and intensity, increased. No one could indulge in sound sleep in the neighborhood of the volcano. Cannonading and trembling developed till the introductory explosion took place. Among the several hundred

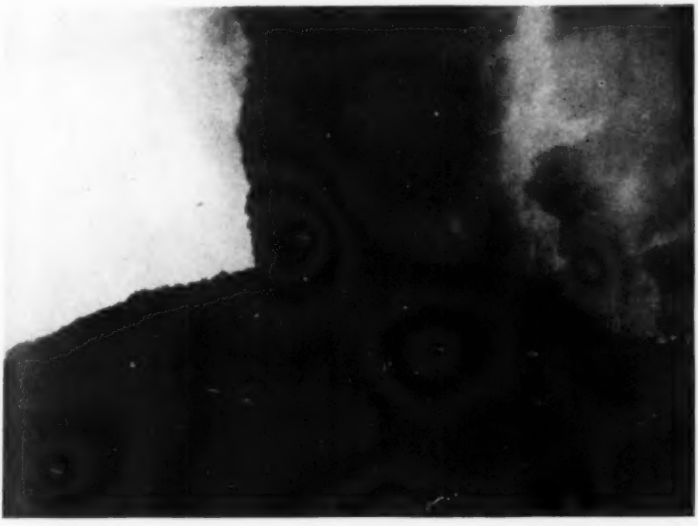

FIG. 11.—A great column of smoke at the top of Nishimaruyama beyond the steaming mud flow. Taken August 2, 1910.

earthquakes two violent ones are worthy of mention, one at 4:30 P.M. on July 24, and the other at 5:00 P.M. on July 25. Monuments fell, houses were badly damaged, the earth was ruptured, and many mud cones were formed around the volcano (Figs. 2–6). The earthquake wave reached an average radial distance of 65 km. outward from Usu, except in the southwesterly direction, where it reached 140 km. The earth's shaking abruptly decreased after the first explosion, suggesting that strains which had been accumulating were then relieved.

II. EFFECT OF THE EARTHQUAKES

There were several phenomena of interest due to the preliminary earthquakes, such as fissures, faults, and the building of mud cones.

1. *Fissures.*—Many ruptures were made within the circle of severe shaking of the earth, especially on the west side of the

FIG. 12.—South scarp of "graben" at the top of Kompirayama. Taken July 14, 1911.

volcano. The directions of the fissures were almost parallel to the coast line, i.e., northwest to southeast, and their width was from 3 cm. to 40 cm. (Fig. 2). Close to the mountain, on the west side, the direction changed to east-west.

2. *Faults.*—Two distinct faults extending east and west were made on the west foot of the Usu. Stepping down toward the north (downthrow side on the north), the throw of the southern fault measured 30 cm. and that of the northern one 1 m. The former extended about 50 m. and the latter 600 m. in length. On September 2 an additional throw of 1 m. was noticed, developing

numerous small parallel fault fractures besides showing 2 m. of horizontal shifting (Figs. 7 and 8).

3. *Mud cones.*—The mud cones are small mounds of mud and sand, well stratified and laminated. They range in size from several centimeters to three meters in diameter, and are flat and conical in shape, the angle of slope being from 3 to 16 degrees. The smallest cone seen measured 10 cm. in diameter, and the largest

FIG. 13.—North scarp of "graben" at the top of Kompirayama. Taken July 14, 1911.

5 m. (Fig. 5). The height of the former was 3 cm. and that of the latter 60 cm. Great numbers of such cones were formed in the bay at the southwestern foot of the mountain, distributed irregularly upon the tidal flat (Fig. 6). About 200 m. from the shore line there is a row of such cones trending generally northwest-southeast. While this row of cones is roughly parallel to the shore line, and consequently fairly straight, there are numerous bends in the line. From the structure of the cones it follows that there must have been a periodical eruption of the sand and mud. The laminations, ranging from 5 mm. up to 3 or 4 cm., are roughly proportional

to the size of the cone, the thicker laminae being found in the larger cones. As is usual with all the cones of this region, it was cold water that issued from them before the eruption of the volcano.

On the north side of Usu a few cones were found on the flat farm land at the foot of the mountain. At no other place in the neighborhood were these phenomena observed. All the cones were

FIG. 14.—Step fault at the west foot of Kompirayama. Taken August 18, 1910

formed by the first severe earthquake, which occurred at 4:30 P.M. on July 24, 1910. The phenomenon is not a peculiar one, for such cones have been reported at many places where strong earthquakes have taken place. They are invariably located along the crack formed by the earthquake where the ground-water issuing through the newly opened vent brings sand and mud with it to the surface. After the eruption of the volcano the mud cones ceased to be active and were gradually obliterated by the process of erosion.

4. *Rise of the water-level in near-by wells.*—Practically all the wells in the neighborhood of the volcano showed a rise in the

water-level; very few showed a decrease. In most cases it was noted that the water in the wells increased to about double the normal volume, while at the same time it became turbid and dirty, owing to the particles of dry mud which fell from the wells into the water below. The rivers of the region also became brown and turbid from slumping of the clay banks. On the southeast side of the mountain several new springs were formed which are still flowing.

III. EXPLOSIONS

After July 22 frequent earthquakes took place, their intensity and numbers increasing hour by hour till 10:00 P.M. on July 25, when the first explosion took place on the northwest side of Kompirayama, a parasitic cone, on the northwest slope of the main volcano (Fig. 9). For a few hours red-hot bombs were ejected on the north side of the cone and made numberless holes in the roofs of the houses in the near vicinity. When the writer visited the region on the following morning, the vent was entirely free from escaping steam, making it possible for him to descend into the crater. At 2:13 P.M. on July 26, a second explosion, preceded by roaring and trembling, took place 200 m. southeast of the first crater accompanying two small explosions. This explosion ejected black and white smoke to a height of about 700 m. That night the smoke stopped for a few hours, but again, beginning at three o'clock in the morning, the roaring became louder and louder as of strong thunder near by, till four o'clock, when it gradually subsided. Meanwhile frequent earthquakes accompanied the formation of three or four explosion craters. In the afternoon of the next day, July 27, the writer saw the ejection of smoke in two craters east of the crater mentioned above (Fig. 10*a*). At 7:00 A.M.

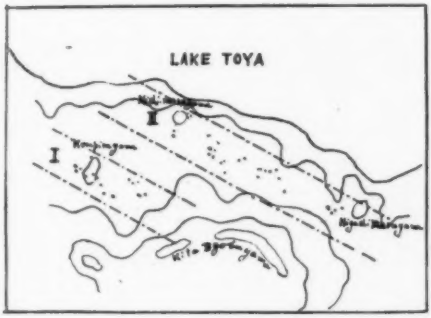

FIG. 15.—Two groups of craterlets. Group I is located at the southwest of Group II.

on July 28, roaring again began, and two explosions took place in sight of the writer at 11:20 A.M. (Fig. 10*b*). The loud roaring continued till eight o'clock in the evening. On the same day there was heavy rain all day accompanied by loud thunder, intense lightning, loud roaring in the ground, and much dense smoke hiding the mountain entirely from view. Before 9:00 A.M. on July 29, judging from the numbers of smoke vents found on that morning, several more explosion craters were formed (Fig. 10*c*).

FIG. 16.—A group of craterlets on the second group. Taken September 4, 1910

On August 2 two new craters were formed at the top of Nishimaruyama, a parasitic cone. For a week these two craters poured forth an astonishing amount of smoke in a large black column such as was not seen from any other cone (Fig. 11). The volume suddenly decreased at the end of one week. Thus in the period of greatest activity, from July 25 till August 2, the number of craters formed amounted to 15. Thereafter, on August 7 and 8, on September 3, and on October 2, small explosions occurred, so that the total number of craters reached 45. Besides these craters numerous crevices and faults developed on the side of the moun-

tain. At the top of the small parasitic cone, Kompirayama, a "graben" was formed about 30 m. in maximum depth, 100 m. wide, and roughly 500 m. in length (Figs. 12, 13). Westward, across the road, the same faulting was found to be "step faulting," with the northern blocks downthrown (Fig. 14). It seems apparent, therefore, that the northern fault of the "graben" is a "scissor fault," reversing its throw on crossing the road. Close to the second group[1] of craterlets, at the same time, were formed many

FIG. 17.—Mud-flow from crater No. VII. Taken August 2, 1910

faults, among which were some forming fault scarps of 5–7 m. in height. The trend of both systems of faults is west-northwest by east-southeast. It is noteworthy that such a large number of craterlets formed in the ten weeks of the eruption.

1. *Process of explosion.*—The order of formation of these craterlets was as follows: In the beginning a cannon-like sound was heard, the ground cracked open in a straight line in the form of a V-shaped crack (Fig. 9), and white smoke issued from the vent. Then followed black smoke together with sand and ashes.

[1] See Fig. 15.

This is the normal order of eruptions for all the craters. The ashes and bombs ejected from the fissures upon the sides of the crevice, after a day, or at most a few weeks, built up a cone. The rapidity with which the cones were built depended on the size of the orifice and the amount of ejectamenta. The angle of slope of the cones ranged from 15 to 30 degrees, the steeper ones being made of the rather coarse material. As the cones grew, the old vents became quiescent and new ones broke out on the side of the

FIG. 18.—"Puff cones" on the mud-flow. Taken August 19, 1911

cone, and the ejectamenta, filling the old crater, sometimes obliterated it.

The life-history of the different cones was not the same, some of them becoming quiescent after only one explosion, others continuing for several days to roar and emit black smoke and to build cones. Some of them emitted smoke intermittently, being active for a few days and then quiet for a few days and then active again, etc. Besides the smoke, ashes, sand, and bombs, a large amount of mud[1] flowed from five of the craters.

[1] *Jour. Geol.*, XXIV, No. 6.

2. *Explosion craters.*—The 45 craters are arranged in two groups (Fig. 15). The first, consisting of 16 craters lying north-northwest of Mount Usu, is aligned in a west-northwest to east-southeast direction. The second group, lying 800 m. northeast of the former, is composed of 29 cones lying in a line parallel to the first group (Fig. 16). The altitude, date of formation, size, shape, and the life-history etc., of each cone in the two groups are tabulated in Table II.

FIG. 19.—Ejection of smoke from crater No. XLII. Taken August 3, 1910

The formation of the cones apparently has no order, though a few in the first of the groups described above formed in sequence, starting from the northwestern end and proceeding toward the east. But in general the action was begun in the first group and finished in the second group.

3. *Ejectamenta.*—Ash, sand, and bombs, with SO_2 and H_2S, were ejected in the black smoke and carried to the lee by the wind, some of the ashes quite a distance. From the first explosion ashes were carried 44 km. toward the northwest of the Usu. Later, ashes from a later eruption were carried 4 km. toward the east and 20 km.

TABLE II

No.	Date	Time	Order	Altitude	Crater		Cone			Remarks
					Shape	Diameter	Depth	Height	Slope	
				m		m	m	m		
I	Aug. 8	2:30 P.M.	13	225	Round	15	5	15	30°	
II	Aug. 8	?	13	245	Round	15	7	7	30	
III	Aug. 8	?	13	250	Round	31	15	0	0	Steaming until May, 1911
IV	July 26	2:13 P.M.	2	270	Ellipse	36×30	13	0	0	
V	July 25	10:00 P.M.	1	240	Ellipse	91×13	18	0	0	Issues smoke and ejects ashes and bombs for a few hours
VI	July 26	2:13 P.M.	2	275	Round	24	9	0	0	Smoke high up to 1,000 m.
VII	July 26	2:13 P.M.	2	275	Ellipse	42×33	10	0	0	
VIII	July 28	.....	5	205	Round	22	2	7	30	Mud-flows
IX	.....	.....	.....	220	Ellipse	36×22	13	0	0	
X	.....	.....	.....	220	Round	10	7	0	0	
XI	.....	.....	.....	220	Round	18	9	0	0	
XII	.....	.....	.....	190	Round	15	15	0	0	
XIII	July 29	8:00 A.M.	9	240	Round	91	35	0	0	Emits black smoke daily until beginning of August
XIV	.....	.....	.....	255	Round	45	16	0	0	
XV	.....	.....	.....	255	Round	16	5	0	0	
XVI	July 27	3:00 A.M.	4	250	Round	27	9	4	20	Crater opens toward west
XVII	Aug. 8	Morning	12	160	Round	36	14	9	26	
XVIII	July 28	5:30 P.M.	7	160	Round	100	18	0	0	Crater opens toward west and mud-flows in great quantity
XIX	Aug. 2	3:00 A.M.	11	160	Round	18	7	0	0	Big black smoke for a week
XX	Aug. 2	3:00 A.M.	11	160	Round	23	9	0	0	Big black smoke for a week
XXI	Aug. 2	3:00 A.M.	11	160	Ellipse	40×18	16	0	0	Big black smoke for a week
XXII	.....	.....	.....	210	Ellipse	69×18	32	0	0	Still steaming
XXIII	July 29	5:00 A.M.	8	210	Ellipse	82×42	16	0	0	
XXIV	.....	.....	.....	240	Round	93	40	9	20	Most active in the beginning of September
XXV	Oct. 2	.....	14	220	Round	130	80	0	0	The second largest crater and the most active
XXVI	July 29	5:00 A.M.	8	250	Round	84	38	18	32	Most active in the beginning of September
XXVII	July 28	5:30 P.M.	7	250	Ellipse	50×47	24	18	25	
XXVIII	.....	.....	.....	240	Ellipse	50×36	11	20	24	
XXIX	.....	.....	.....	230	Ellipse	27×15	7	0	0	
XXX	.....	.....	.....	220	Round	90	18	5	20	
XXXI	.....	.....	.....	250	Round	51	29	31	30	Much ejectamenta, and completes the cone on August 13
XXXII	.....	.....	.....	210	Round	76	40	15	20	Steaming on the north wall in the crater
XXXIII	July 26	11:30 P.M.	3	205	Round	64	30	18	18	Mud-flows on July 29, and still steaming
XXXIV	.....	.....	.....	200	Round	31	9	18	28	
XXXV	.....	.....	.....	200	Ellipse	70×20	18	10	20	
XXXVI	.....	.....	.....	200	Ellipse	85×70	37	0	0	More active than XXXV and XXXVII, and overlaps them by ejectamenta
XXXVII	.....	.....	.....	190	Ellipse	54×22	11	0	0	
XXXVIII	.....	.....	.....	190	Round	69	37	23	32	
XXXIX	July 27	3:00 A.M.	4	165	Ellipse	62×40	6	15	25	Mud-flows and partly overlapped by ejectamenta of XXXVIII
XL	July 28	11:20 A.M.	6	175	Ellipse	69×40	10	0	0	
XLI	July 28	11:20 A.M.	6	220	Ellipse	70×60	30	10	20	Crater opens toward east
XLII	July 29	9:00 A.M.	10	220	Ellipse	210×150	90	50	30	Three craters unite and make the largest pit, mud-flows and the most active
XLIII	July 29	9:00 A.M.	10	170	Ellipse	70×24	11	0	0	Crater opens south
XLIV	July 29	9:00 A.M.	10	160	Round	22	7	0	0	
XLV	.....	.....	.....	155	Ellipse	20×10	0	0	0	

toward the south, the amount being greatest on the northwest side of the mountain. In the Kompirayama region the ashes that fell formed a layer up to 8 and 10 cm. in thickness, while at the distance of 1 km. from the mountain thicknesses of 3 mm. to 1 cm. were found. On the north side of the second group of cones, a general thickness of 1 cm. was found, while at their very foot the layer was 30 cm. in thickness. But on the east side and south side of the mountain

FIG. 20.—Bombs and mud-flow from crater No. XLII. Taken July 31, 1910

very little ash was found. Besides the ash, sand, and bombs, from five of the craters mud and hot water were ejected. Among these five craters No. VIII was the first to erupt (Fig. 17), while No. XIII ejected the largest quantity of mud (Fig. 11). From the craters to the lake is an expanse of mud which flowed out to a width of 200 m., a length of 500 m., and a thickness of 1.5 m. In addition to this great quantity of mud on the land there was a large amount that flowed into the lake. The mud is composed of fine, gray-colored plagioclase, hypersthene, augite, and magnetite, with a

small amount of hematite, together with glass in an amount comparable with that of the feldspar. Cone No. XVIII ejected the mud periodically in a geyser-like fashion. The mud contained a large amount of gas which came to the surface of the mud-flow after it had almost solidified, making "puff cones"[1] in great numbers (Fig. 18).

The materials of the mud-flows, the sand of the seashore, and the substance in the mud cones mentioned above, when compared

FIG. 21.—Heavily burdened trees near the craters. Taken October 16, 1910

under the microscope, were found to be identical in composition. The fineness, however, is variable; the size of grains in the beach sand being the largest, that in the mud cones intermediate, and that in the mud-flow the finest. The base of the volcano Usu is composed of brown pumice, uniform in constitution throughout the whole region, and the fact that the mud-flows, the cones, and the sand of the beach are alike in composition suggests that they all came from some common source, which in all probability lies horizontally and extends not much below the level of the sea.

[1] *Jour. Geol.*, XXIV, No. 6.

From craters Nos. XXV and XLII great quantities of bombs and sand were intermittently ejected to a height of 700 m. (Figs. 19, 20). The ejected bombs and ashes frequently took the shape of serrate peaks and pinnacles which rose alternately to great heights and then sank back as another one shot up. It was noticed that descending bombs, when struck by rising ones, produced loud reports like the explosion of firecrackers. White, comet-like tails followed the bombs into the air. The largest bomb measured

FIG. 22.—Houses inclined 12° owing to the elevation of the left-hand side. Notice a man standing straight. Taken September 4, 1910.

was 25 cm. in diameter and was of the characteristic irregular and rounded shape. The largest hole noted, formed by a falling bomb, was 3 m. in diameter by 2 m. in depth.

Petrography of the bombs (*augite-hypersthene-andesite*).—The bombs ejected from the several craterlets are quite similar, though the percentages of the constituent minerals are slightly different. A brief description follows:

Megascopically, the bombs are dark gray, porous, roundish in shape, and less than 25 cm. across. The pores are very abundant at the surface, slightly less numerous within, and range in diameter

from 1 mm. to 2 cm. The majority of the pores are filled with ashes and sand. Phenocrysts of white plagioclase, which do not exceed 3 mm. in size, produce a porphyritic texture. There are also crystals of dark-colored pyroxene, but they are small and not abundant.

Microscopically, the rock has a hyalopilitic-porphyritic texture. The groundmass consists of dark-brown glass with minute crystals

FIG. 23.—New elevated mountain seen from the east. Taken December 23, 1910

of plagioclase, augite, and hypersthene, and the phenocrysts of colorless plagioclase and green pyroxenes.

Plagioclase is the chief constituent. It is either tabular or equidimensional, and polysynthetic twins and zonal structures are remarkably well developed. Zonally or irregularly included in some of the crystals are patches of brown glass and minute grains of pyroxene.

The extinction angle on the *M* face of the plagioclase is between $-28°$ and $-30°$, and the maximum extinction angle in the symmetrical zone is $+32°$, showing it to be labradorite.

The hypersthene has a slender prismatic habit and strong pleochroism, green to reddish brown.

Augite is usually small in size, mostly in the groundmass.

The rock may be formulated as follows:

$$\frac{P_{40}}{G_{60}} = \frac{Lab._{.28}+Hyp._{.8}+Aug._{.4}}{Glass_{36}+Lab._{.18}+Hyp._{.3}+Aug._{.3}}$$

P_{40}, 40 per cent of phenocryst.
G_{60}, 60 per cent of groundmass.
Lab., labradorite.
Hyp., hypersthene.
Aug., augite.

Chemical composition.—The rock is rather basic, low in SiO_2, high in Al_2O_3, CaO, and iron, so that some might call it basalt. The writer found a great similarity in mineralogical and chemical composition between the bomb and the lava which forms the old crater ring of the main volcano, as shown by Table III, which gives an analysis of the bombs, with other similar rocks for reference.

TABLE III

	I	II	III	IV	V	VI	VII	VIII
SiO_2	52.40	51.86	51.88	51.32	50.16	52.02	52.86	51.12
Al_2O_3	17.59	21.69	21.53	17.84	17.97	17.14	18.25	19.59
Fe_2O_3	3.51	4.46	2.45	4.34	2.23	7.96	6.61	2.86
FeO	7.07	5.39	6.36	6.70	6.25	3.52	3.39	6.53
MgO	3.73	2.87	2.08	4.18	4.70	3.13	4.27	4.47
MnO	0.16	0.29	0.20	.....	0.30	tr.	0.16	0.65
CaO	9.36	10.37	11.09	9.51	11.85	11.57	9.58	9.54
K_2O	1.77	1.08	1.56	1.52	2.80	0.60	0.69	0.57
Na_2O	2.93	2.02	3.12	3.01	3.50	2.38	3.24	3.11
H_2O	0.57	0.26	0.17	1.98	.....	0.28	0.69	0.11
TiO_2	1.06	.....	.....	.....	.....	.....	.....	0.86
P_2O_5	0.14	.....	.....	.....	.....	.....	.....	0.14

I. A bomb from Usu, analyzed by *Bulletin of the Imperial Geological Survey of Japan*, XXIII, No. 1.
II. Mean value of three bombs, analyzed in the laboratory of geology in the Agricultural College, Sapporo.
III. Lava of old crater ring on Mount Usu, analyzed in the same laboratory.
IV. Luciite, Luciberg, Odenwald Hesse.
V. Augite-andesite, Kilauea, Hawaii.
VI. Basalt? Yate Volcano, Patagonia.
VII. Pyroxene-andesite, Choa-shen, Kamchatka.
VIII. Basalt, Goentoer lava, Java.
III to VIII taken from J. P. Iddings, *Igneous Rocks*.

IV. DAMAGE

By the fracturing of the earth and the explosions, the deep, beautiful forest on the slopes of the mountain was destroyed. The leaves were all stripped from the trees, the greater number of

which were broken and shattered. Many were blown out of the ground by the explosion, while others were buried and broken by the fall of bombs and ashes (Fig. 21). The bombs, however, were not thrown more than 500 m. from the craters, but the sand and ashes were driven to a distance of several kilometers. Often heavy showers of sand and ashes were seen to fall in localized areas, in many places forming long strips of débris on the land. At one place in a field of barley the strip measured 3 m. wide and was traced for a distance of 200 m. While in the air these masses of ejectamenta looked like a jet of water issuing from a hose. This effect was produced by air currents concentrating the material into long lines. The damage done by falling ash, including injury to farm land as well as destruction of houses, etc., was heavy within a radius of 2 km. of the craters. The most severe damage by ash and mud-flow amounted to 3 sq. km. of land covered. Five houses were carried down to the lake by the mud-flow, and a few houses were buried by the heavy ashes, while five other houses were shattered as a result of the local undulation of the land. At Abuta, a distance of 4 km. from the nearest crater toward the northwest, a monument and a small house fell, together with three brick walls (Figs. 1, 3, 4) and two plaster ones of a storehouse. In the same village many cracks developed in the walls of the houses.

V. CHANGE OF TOPOGRAPHY

On July 28 the writer found the rise of the water of Lake Toya on the north side to be about 30 cm. On August 6 Dr. Omori found a lowering of the water-level on the south side of the lake. From August 20 it was noticed that the north side of the second group of craters began to rise. This elevation (155 m. high from the lake-level, according to Professor F. Omori) continued till the end of November. The slope of the southern shore of the lake was about 5 degrees. It then gradually rose to a slope of 30 degrees at the top of the elevation, and 22 degrees on its flank. A photograph taken by the writer on September 4 shows a house which, originally constructed upright, was then inclined 12 degrees from the vertical. Two days later this house had collapsed (Fig. 22). Before the

eruption the cone Nishimaruyama could be seen from the village of Nishikohan, but as a result of the elevation which took place the view was obstructed. The area of elevated land is about 2 km. in length by 1 km. in width to the edge of the lake, and, judging from soundings made, it extends another kilometer under the water (Fig. 23). The maximum height of the elevation measured about 120 m. (Figs. 24, 25, 26).[1]

FIG. 24. Mountain slope in the beginning of eruption. Taken July 29, 1910

Mr. Ito, of the Sapporo Meteorological Observatory, found a lowering of 36 m. on the top of the new mountain in April, 1911, while Mr. Iizuka, of the Imperial Geological Survey, recorded 43 m. lowering in July, 1911, by an aneroid barometer.

When the gases involved in the lava are expelled in a great quantity, a decrease of volume will take place, and the lowering of the mountain should result from this shrinkage.

[1] This measurement was made by comparing graphically and to scale the photograph taken before the elevation with that taken afterward. This checked well with the reading of the aneroid barometer which nearly coincides with the map of the Imperial Geological Survey of Japan.

Furthermore, there is a remarkable change of height in Usu proper, as is shown by the map of the Imperial Geological Survey, July, 1911. In the topographical map published by Hokkaidocho, the height of O-usu is recorded as 595 m. and that of Ko-usu as 580 m., while the Imperial Geological Survey reports 736 m. and 609 m. respectively. This difference is too great to be regarded as an error in surveying and must mean that some igneous intrusion produced the irregular change of elevation. The writer presumes that the present height of Usu would be found to differ materially from that recorded by the Imperial Geological Survey.

One year after the eruption Dr. Omori[1] observed that there were local elevations and depressions of the ground in the vicinity of the mountain and over an area of 150 sq. km. The Military Survey Department undertook the determination of height at the request of Dr. Omori and found that Mount Usu was raised, while the western foot was depressed. In the following year the same surveyor recorded contrary results; that is, the previously elevated portion had been depressed, while the depressed part was uplifted.

VI. SUMMARY

1. *Earthquakes and roaring before an eruption.*—As a rule the eruption of Usu is preceded by the foreshocks. This, in the opinion of the writer, suggests that the lava reservoir was located nearly at the same depth in the case of the recent eruptions. The magma in the reservoir, becoming highly heated, could not retain the involved gases, and so the maximum strain under the crust was produced by the continuous heating process. The explosion took place when the interior and exterior pressures were not counterbalanced. Thus the pressure of the highly heated magma overbalanced both the atmospheric and the crustal pressures. The ground beneath the surface burst, owing to the intense strain, and produced the loud sound. The speed of the earthquake waves is greater than that of the sound traveling in the ground and the air. The minute tremor which normally precedes the sound was not noticed because there was no seismograph at hand. Hence,

[1] *Bulletin of the Imperial Earthquake Investigation Committee*, V, No. 3 (1913).

in a seemingly contradictory fashion, the large tremor of the earthquake was felt after the sound was heard.

2. *Least resistance.*—From the structural point of view the greatest number of fractures were observed along the sides of the great depression, or along the anticlinal top; and especially large fractures were found close to the edge of the depression. On the coast line of the Pacific Ocean the presence of several volcanic

FIG. 25.—"New Mountain" almost completed. Taken October 25, 1910

zones naturally demonstrates the existence of fractures made by the depression of the Pacific basin. Two recent faults in the vicinity of Usu were made by the earthquakes, many fractures usually accompanying the fissures along the aperture. Coming back to the original Lake Toya, the writer believes that the depression of the ground produced the lake, which is surrounded by comparatively sharp cliffs; as T. Kato stated in his report,[1] there must have been some fractures along the margin of the lake through which Mount Usu erupted. Such fissures, the writer dares to say,

[1] *Report of the Imperial Earthquake Investigation Committee*, No. 62.

are the weak lines around the foot of Mount Usu. The gases involved within the magma found an exit through the old fissures, the lines of the least resistance, which existed under the lava-flow, and thus the two fissure zones, parallel to the shore line of the lake, were made. As in the case of a viscous substance which is being boiled and shows the evolution of gases in certain restricted points which migrate around over the surface of the liquid, we may assume that the gases evolving from the magma are generated at different

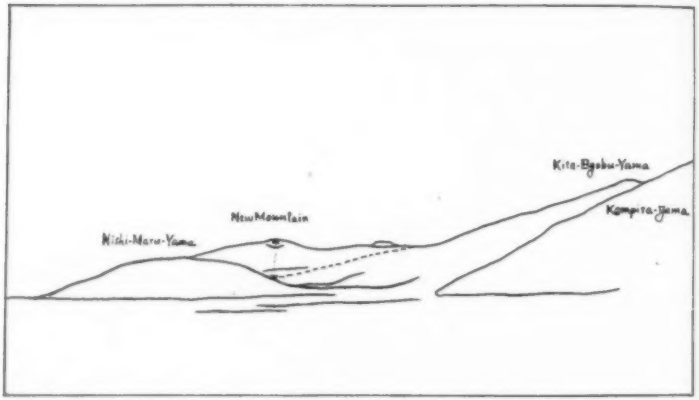

FIG. 26.—Topographical comparison of the north side of the Usu. Broken line, the slope before the elevation. Taken July 29, 1910. Full line, the present relief. Taken October 25, 1910. Dotted line, the actual difference of altitude.

places without reference in time to each other. The irregular eruption of the craterlets may be explained on this hypothesis.

The independent activity of the new craterlets to the old, small, steaming pits on the O-usu and Ko-usu suggests by their lack of sympathy that they do not rise to the surface through the same lava vents and that the reservoirs are not connected.

3. *Origin of the "New Mountain."*—Professor F. Omori[1] stated that the "New Mountain" is due to the intrusion of lava in the form of a spine or dome, and Professor D. Sato[2] believes the intru-

[1] *Bulletin of the Imperial Earthquake Investigation Committee*, V, No. 1, p. 1.

[2] *Bulletin of the Imperial Geological Survey of Japan*, XXIII, No. 1 (1913).

sion to be a laccolith. Many geologists agree with the theory of G. K. Gilbert as to the formation of the laccolith. It is a plausible supposition that the propelling magma would find the line of least resistance in certain planes, lifting the land above it. In the early stages of the activity in Mount Usu enormous quantities of gases were emitted, together with ashes and bombs, while at the mature stage the north side of the second zone of craters was sharply elevated in a straight line. Ernest Howe[1] made experiments on the intrusion of wax into plaster, marble, sand, and coal layers, and demonstrated how the laccoliths are formed. Where there are fissures from the inner source to the surface, there must be a line of least resistance at this place. Intrusion between the strata occurs only where there are no fissures or cracks extending to the surface. It is unreasonable to believe in the intrusion of the laccolith while the distinct cracks shown in the two zones of craterlets are in evidence, as we have seen in the experimental data of Howe. The majority of nearly 150 laccoliths in the western part of the United States of America are composed rather of acidic rocks, while rock[2] as basic as that of Usu is found only in rare cases. The basic lavas preserve a comparatively high degree of liquidity down to rather low temperatures, with a quick process of solidification by rapid crystallization, as is well illustrated in blast-furnace slag. Ejection of many bombs demonstrated that the lava was not seated in the great depths.

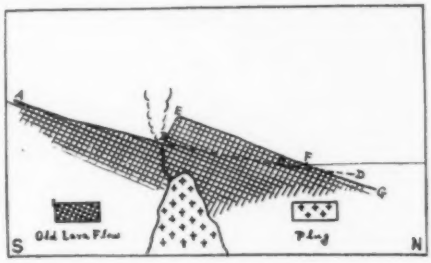

FIG. 27.—A diagram showing the intrusion of "plug": *A*, *B*, *C*, *D*, mountain slope before the eruption; *B*, *E*, *F*, elevated mountain; *C*, shore line before the eruption; *F*, present shore line.

From the facts stated above, the writer is inclined to believe that the formation of a "plug," elongated west-northwest by east-

[1] *Twenty-first Ann. Rept., U.S.G.S.*, Part III (1901).

[2] See the analysis of bomb.

southeast and elliptical in plan, took place in the midst of the activity. Of course, we must not forget that the elevation is not entirely due to the intrusion of the plug, but that there was co-operation of the faulting such as is so remarkably shown on the top of Kompirayama. The elevation of the lake shore on the south side of Lake Toya may be accounted for by the tilting of the crust owing to the intrusion of the plug rather than, as previously supposed, to the formation of a laccolith (Fig. 27). From dynamic considerations it is evident that if the force of the plug intrusion be applied to one end of a resistant section of the earth's crust the whole block will be lifted and tilted.

How could such a very steep slope (40°–70°) on the south side and 22°–30° on the north side be made on the surface by the intrusion of a laccolith? If we suppose that there is a very sharp, steep dome in the great depth overlaid by heavy layers above, its inclination becomes gradually gentle toward the surface, unless the crust be in the liquid or semiliquid condition.

4. *Undulation of ground near Usu.*—From the damage done, and from faults, fissures, and mud cones which were found exclusively on the same side, we may prove that the structure of the western region was originally weak, so that the shaking was intense, while in other parts the effects were comparatively small. Frequent explosion also weakened the already feeble lines.

We may then conclude, from evidence gathered in the field, that there must have been intruded irregular bodies of lava that produced the undulation of the ground near Usu recently observed in the eruption.

INTRAFORMATIONAL PEBBLES IN THE RICHMOND GROUP, AT WINCHESTER, OHIO

AUGUST F. FOERSTE
Dayton, Ohio

Ripple-marks, measuring two feet or more from crest to crest, occur at numerous horizons in the Ordovician rocks of Ohio, Indiana, and Kentucky, but are abundant especially in the middle parts of the Richmond group, where they characterize the upper part of the Waynesville formation and the lower part of the immediately overlying Liberty formation. Among the occurrences of ripple-marks discussed by Prosser, in his recently published paper on the "Ripple-Marks in Ohio Limestones,"[1] the following belong to the lower part of the Liberty formation: Elk Run, a little over a mile east of Winchester, Ohio (Figs. 1, 2); Cherry Fork, at Harshaville, 6 miles east-southeast of Winchester; and Treber Run, 5 miles southeast of Harshaville. The ripple-marks described by Joseph Moore and Allen D. Hole from a small western tributary of the Whitewater River, 5 miles southwest of Richmond, in Indiana, and those described by W. P. Shannon from the bed of Salt Creek, 3 miles west of Oldenburg, 38 miles southwest of Richmond, also occur in the lower part of the Liberty formation. At the Ridenour Mill, $5\frac{1}{2}$ miles northwest of Oxford, Ohio, the ripple-marks described by Nelson W. Perry[2] occur both in the lower part of the Liberty and in the upper part of the underlying Waynesville formation. In fact, over a large part of Ohio and Indiana, ripple-marks are fully as abundant in the upper part of the Waynesville as in the lower part of the Liberty, and the list of localities might be multiplied almost indefinitely. Ripple-marks occur also near the top of the Brassfield formation at numerous localities in southern Ohio (Figs. 3, 4) and northern Kentucky, east of the Cincinnati axis.

[1] *Jour. Geol.*, XXIV, No. 5 (1916), pp. 456–57.

[2] *Am. Geol.*, IV (1889), 326–36.

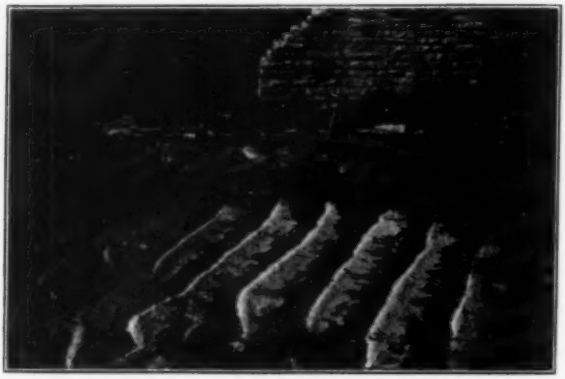

FIG. 1.—View of ripple-marked limestone in bed of Elk Run, looking northward toward abutment of road bridge. The appearance of strong contrast in the slope on opposite sides of the ripples is due to the dip of the rock toward the right causing the water to rise higher on the left side of the crests. In reality, the difference in slope on the two sides is small.

FIG. 2.—View at the same locality, looking northeast across the stream. See also Fig. 2, on p. 460 in *Journal of Geology*, XXIV, No. 5 (1916).

FIG. 3.—Ripple-marks on Brassfield limestone in Beasley Fork, a mile and a quarter south of West Union, Ohio. Note the small difference in slope on the two sides of the ripples.

FIG. 4.—Ripple-marks at the same locality and horizon on Beasley Fork

Occasionally pebbles occur in the ripple-marked layers of limestone. These pebbles usually are few in number and rarely are sufficiently abundant even to suggest the term conglomerate. They are more abundant at two horizons in the lower part of the Liberty formation at the locality on Elk Run, east of Winchester, Ohio, described by Prosser, than at any other localities known at present in the Ordovician of Ohio, Indiana, and Kentucky, and therefore this locality has been chosen to present some of the features characteristic of these pebbles. The pebbles are of two types.

1. In one type the rock is very fine-grained, as though originating from a calcareous mud, and is frequently marked by worm-burrows. There are also peculiar gouged-out markings, 3 or 4 mm. wide, 60–100 mm. long, often 20 mm. deep at the center, curving downward from the ends toward the center as though carved out by some narrow gouge. Markings of this kind frequently connect the two oblong or nearly circular terminals forming the peculiar dumb-bell fossil called *Arthraria*. There are also gouged-out markings only an inch in length (Fig. 6, pebble *C*). The surface of these pebbles often is very irregularly rounded, as though the rock had been soft at the time of formation of the pebbles. At one horizon these pebbles frequently support small colonies of the incrusting coral *Protarea richmondensis* (Fig. 5), 40–70 mm. in width. In fact, twenty pebbles supporting *Protarea richmondensis* were exposed along a narrow outcrop, a foot wide and scarcely 50 feet long, at the time of my last visit. Young specimens of *Streptelasma*, presumably *Streptelasma rusticum*, 10–15 mm. in length, occasionally occur, attached by their sides to the pebbles. Three pebbles supporting young specimens of *Streptelasma* occurred in the 50-foot length mentioned above. Incrusting growths of *Dermatostroma corrugata* and of various thinly incrusting bryozoans also occur occasionally. Since the incrusting growths follow the irregular curvature of the pebbles, it is evident that the latter is not due to subsequent erosion. In one specimen, thinly incrusting bryozoans and growths of *Stomatopora* occur on the lower side of the pebble, while thicker growths of *Protarea richmondensis* occur on the upper surface, showing that the pebble had been turned over at least once.

The fine-grained mud of which these pebbles are composed incloses but few fossils. In three pebbles *Lophospira bowdeni* was found, and one pebble contained a ventral valve of *Dinorthis subquadrata*, a characteristic fossil of the Liberty formation, unknown in the underlying Waynesville strata. In other words, there is no reason for believing that the rock of which the pebbles are composed is older than that of the formation in which the pebbles now occur. In fact, at several localities along the creek, the rock immediately underlying the pebble-bearing layer is sufficiently similar to the rock forming the pebbles to have given origin to the latter.

These fine-grained pebbles usually do not exceed 6 inches in length, 3 inches in width, and an inch in thickness, but specimens 12 inches long, 7 inches wide, and 2 inches thick are known, and one pebble 18 inches long, 11 inches wide, and 3 inches thick was observed.

2. The second type of pebbles usually consists of a fine-grained blue limestone, in which the grain is distinctly less fine than in the first type. The granular structure usually may be recognized without the assistance of a magnifier. Worm-burrows usually are absent, and no incrusting bryozoans or specimens of *Protarea* have been observed. The color of the rock is bluish gray, similar to that of the inclosing rock, and the outlines of the pebbles may be distinguished from the latter chiefly by the finer grain of the rock forming the pebbles, and usually also by differences in the stratification planes running through the rock. Such fossils as occur in these pebbles suggest the Liberty age of the rock from which the latter were derived, and the source of this rock could have been one of the underlying layers within this formation.

The pebbles of this second type usually are relatively thin and flat. The upper and lower surfaces usually are parallel, the lateral margins often being vertical or rounding only moderately into the upper and lower surfaces. In vertical cross-sections, therefore, the pebbles appear angular at the margins. Angularity frequently characterizes also the lateral outlines, as observed from above. In other words, the pebbles frequently appear broken off from thin layers of limestone, without much rounding. Some of

the pebbles are only 4 inches in length, and only a few exceed 12 inches in length, 7 inches in width, and 1 inch in thickness, but occasionally specimens much larger than this are seen. One

FIG. 5.—Pebble, of natural size, supporting two colonies of *Protarea richmondensis*. From layer D in the Elk Run section, east of Winchester, Ohio.

FIG. 6.—Limestone slab, of one-third natural size, supporting several pebbles; of these the one represented by Fig. 5 is located at *A*, but in an inverted position. From layer D in the Elk Run section, east of Winchester, Ohio.

pebble 38 inches long, 28 inches wide, and 2.5 inches thick was found.

The relative position of the pebble-bearing layers among the ripple-marked limestones along Elk Run may be seen from the following section. Ripple-marked layers occur here at various levels in a section at least 30 feet thick. Owing to the fact that the dip of the rocks is in the same direction as the flow of the stream, several layers disappear below the level of the stream at one point and reappear farther down the stream. This makes the unraveling of the section more or less difficult in places, but the following section, described in descending order, is as nearly correct as may be determined from the present condition of the exposures, which is unusually favorable for this locality.

SECTION ALONG ELK RUN, 1.5 MILES EAST OF WINCHESTER, OHIO

		Ft.	In.
Layer A.	Exposed about 600 feet south of railroad bridge; crest of ripples running N. 47° W. Pebbles few.		
Interval		5	
Layer B.	Crest of ripples running N. 40° W.		
Interval		3	9
Layer C.	Crest of ripples running N. and S.		
Interval			9
Layer D.	Crest of ripples running N. 40° W. This layer is not ripple-marked southeast of the home of Charles Bailey, but here numerous fine-grained pebbles, many supporting growths of *Protarea richmondensis*, occur (Figs. 5, 6).		
Interval		1	
Layer E.	Crest of ripples running from N. 30° W. to N. 25° W.		
Interval			9
Layer F.	Crest of ripples running N. 35° W.		
Interval		1	6
Layer G.	Crest of ripples varying from N. 3° W. to N. 15° W. at the small fall northeast of the home of Charles Bailey. This layer is exposed also immediately north of the road bridge, and between the road bridge and the railroad bridge. It is characterized by angular, flat pebbles, few in number, but sometimes of considerable length and width, considering the small thickness.		
Interval		6	

		Ft.	In.
Layer H.	Crest of ripples running N. 15° W.		
Interval		5	
Layer I.	Crest of ripples running N. and S., faintly defined. Near home of E. E. Jamison.		
Interval		5	
Layer J.	Poorly defined ripple-marks, at next house on west side of creek.		
Interval		1	
Layer K.	Crest of ripples running N. 70° E.		
Interval		1	
Layer L.	Crest of ripples running N. 50° E.		

The fine-grained pebbles first described, apparently consisting of a lime mud, supporting incrusting growths of *Protarea*, *Dermatostroma*, and various species of bryozoans, are specially characteristic of layer D. This layer is exposed at several localities along the creek, but the pebbles are common only southeast of the home of Charles Bailey, on the eastern side of the creek. Here the pebbles rest upon the top of the layer or are more or less imbedded in its upper part. This pebble-bearing layer is exposed also farther up stream, about 500 feet north of the road bridge. Here the pebbles vary from 2 to 4 inches in length, and from a quarter to half an inch in thickness. Farther up stream, immediately south of the road bridge, this layer is strongly ripple-marked, the crest of the ripples running N. 40° W. One pebble was noticed here 14 inches long, 7 inches wide, and half an inch thick. Farther north, where the pebbles are abundant, ripple-marks are absent.

The less fine-grained and more angular blue limestone pebbles, described last, occur in layer G. This layer is exposed between the railroad bridge and the road bridge, a short distance northward. The crests of the ripple-marks vary here (Figs. 1, 2) between N. 3° W. and N. 15° W. in direction, and on the average are about 30 inches apart. The following pebbles were noticed here, imbedded within the upper part of the ripple-marked layer, only the upper surface being exposed. In each case the length, width, and thickness of the pebble are given. One pebble, 4×3×0.5 inch, lay in a trough and sloped gently toward the west. Another, 12×7×0.5 inch, lay in a trough in a horizontal position. Two pebbles, 4×4×0.25 inch, lay in a trough and sloped toward the east. Two pebbles,

4 inches in transverse diameter, lay in a trough in a horizontal position. One pebble, 8×5×0.5 inch, was imbedded on the eastern side of one of the crests, but in a horizontal position. Two pebbles, one on the eastern and one on the western side of the same crest, were in a horizontal position. The steeper side of the ripple-marks lies on the western side of the crests. The same layer is exposed immediately north of the road bridge, with layer D about 3 feet 3 inches farther up.

Layer G is exposed again at the small waterfall northeast of the home of Charles Bailey. The crests of the ripple-marks here run N. 3° W., the crests are about 28 inches apart, and the steeper slope is on the western side. Here the following pebbles were noticed, the dimensions being given in inches: one pebble, 10×7×1 inch, in a horizontal position, imbedded along the crest of one of the ripples; a pebble, 12×7×1 inch, in a horizontal position, buried under the western half of a crest; a pebble, 38×28×2.5 inches, in a horizontal position, imbedded so that its upper surface is on the same level as that of the surrounding rock. The moderately rounded margins are slightly overlapped by the surrounding rock; and the ripple-marks characterizing the latter are clearly defined as far as the margin of the pebble, but are absent, of course, on the surface of the latter.

Layer G is exposed also farther down the stream, northward. Here the crests of the ripples run N. 15° W., both sides of the ripple-marks sloping equally. One pebble, 6×4×1 inch, was imbedded up to its upper surface within the ripple-marked layer, and an incrusting bryozoan overlapped one margin of the pebble and the adjacent part of the surrounding rock, showing that enough time elapsed before the deposition of the overlying clay bed to admit of the growth of this bryozoan, the thickness of the latter being about 3 or 4 mm.

The pebbles in layer A were few in number. One pebble, 6×4×0.5 inch, consisted of fine-grained rock, resembling the worm-burrowed layer beneath the ripple-marked limestone. Farther north, nearer the railroad bridge, several additional pebbles, consisting of the same kind of rock, were found. The crests of the ripples run N. 47° W., they are 20–30 inches apart, the inter-

vening troughs are about 2.5 inches deep, and the steeper slope is on the western side.

All of the strata included within the 30-foot section here described belong to the Liberty formation. The lowest layer, L, contains the characteristic fossil *Dinorthis subquadrata*, and *Plectambonites sericea* is so abundant here that it suggests a horizon not far above the base of this formation. The abundance of typical *Strophomena planumbona* throughout the section suggests the lower half of the Liberty. *Strophomena vetusta*, associated with *Dinorthis subquadrata* and *Rhynchotrema capax*, is comparatively rare until the layers immediately overlying layer A are reached, but the general aspect of the rock here still is that of the Liberty formation.

Judging from exposures on Graces Run, a little over a mile west of Harshaville, the highest strata exposing ripple-marks occur at least as far up as within 88 feet of the base of the Brassfield limestone. Pebbles up to 6×4×0.5 inch in dimension occur at a small fall half-way between this point and the mouth of Martins Run, half a mile southeastward. Several pebbles occur also in the wave-marked layers in the bed of Cherry Fork, immediately west of Harshaville.

The highest ripple-marked horizon along Elk Run, east of Winchester, appears to be about 80 feet below an exposure of Brassfield limestone seen along the railroad, west of the creek.

Pebbles up to 7×4×0.5 inch in dimension occur also on Treber Run, about a quarter of a mile west of the mouth of the stream, a short distance west of the first crossing of the road following the stream. Here the pebbles occur in large, loose slabs of limestone containing a Liberty fauna, and evidently not transported far. The pebbles consist of small-grained blue limestone, similar to those occurring in layer G in the Elk Run section.

Perhaps the chief reason why the presence of pebbles in these ripple-marked strata has received so little attention is because they are so readily overlooked. By far the larger number of pebbles are horizontal in position, their stratification planes coinciding in direction with those of the inclosing rock. Especially is this true of the larger pebbles, while the smaller pebbles occasionally occur

at distinct angles with the inclosing rock. Moreover, the upper surface of the larger pebbles rarely projects distinctly above the surface of the inclosing rock, but more commonly is about at the same level as the latter. On careless examination, the pebbles appear merely as adhering remnants of the next overlying layer of rock. They are distinguished chiefly by the finer grain of the pebbles, frequently accompanied by a difference in color and by a difference in the character and location of the stratification planes.

There is no evidence that the larger pebbles, a foot or more in diameter, ever were turned over so as to present the lower instead of the upper surface of the original rock stratum. Perhaps this statement could be made with equal accuracy of any pebble 6 inches in width. The largest pebbles, so far found, which give evidence of having been overturned before being imbedded have a width of almost 3 inches, although the length may equal 6 inches. In one of these pebbles, obtained from layer D in Elk Run, a thin growth of *Ceramoporella ohioensis* on one edge of the pebble overlaps both the upper and the lower surface of the latter by fully an inch, and additional growths of the same species occur on the lower surface, the entire width of the pebble being $2\frac{3}{4}$ inches. The incrusting specimens of *Protarea* frequently occur on the upper surface of the pebbles, often several colonies on the same pebble, and these colonies frequently overlap the lateral edges, but never occur on the lower surface of the pebbles.

The size and the angularity of the larger pebbles suggest that they have not been transported very far. The absence of overturning of these larger pebbles also suggests only a short distance of transportation. The very irregular surface features of the very fine-grained pebbles, among which evidences of overturning are more frequent, suggest washed lumps of partly indurated calcareous mud rather than strongly eroded and frequently overturned rock.

Although rock similar to that forming the pebbles frequently occurs immediately below the layer in the upper surface of which the pebbles are imbedded, these ripple-marked layers frequently are continuous over such large areas, as determined from exposures along the lateral branches of streams, as to make the origin of the pebbles from underlying strata more or less doubtful. Especially

is this true in the case of the larger pebbles, which apparently have been transported only short distances.

Moreover, there is no evidence of strong unconformities anywhere in the Richmond series of rocks. At no point has a layer of rock been found to overlap the lateral margins of any of the layers for even a vertical distance of 2 feet. Hence an origin from anything like a cliff or coast or beach seems questionable. At least there is no evidence of the presence of any cliff, coast, or beach sufficiently close to the area in question to have furnished the material for the pebbles.

There was a tendency formerly to regard the presence of ripple-marks as evidence of shallow-water conditions and as suggesting the proximity of shore lines. This found expression in a paper by Joseph F. James on the "Evidences of Beaches in the Cincinnati Group."[1] Here the ripple-marks in the upper part of the Cynthiana formation, at Ludlow and West Covington, Kentucky, opposite Cincinnati, and another set of ripple-marks about 300 feet above low-water mark in the Ohio River, presumably in the upper part of the Eden formation, were interpreted as evidences of the proximity of beaches. As further evidence of shallow-water conditions during the deposition of various parts of the Cincinnati group, the presence of raindrop impressions near the top of the Cincinnati group was cited, but the exact location of the rock bearing these raindrop impressions is not given.

The impression that at least a part of the rocks of the Cincinnati group were deposited in very shallow waters finds expression also in a paper by Nelson W. Perry on "The Cincinnati Rocks; What Has Been Their Physical History?"[2] Here raindrop impressions are cited from the vicinity of Smiley's Dam, $3\frac{1}{2}$ miles southeast of Oxford, but 5 miles distant when approached by the road. The dam is located on Fourmile Creek. The lowest strata exposed belong to the Mount Auburn division of the Maysville formation, and a mile westward the *Dinorthis carleyi* horizon near the middle of the Arnheim bed is exposed at an elevation about 50 feet higher. Careful search by the present writer failed to locate

[1] *Science*, V (1885), 231.

[2] *Am. Geol.*, IV, No. 6 (1889), pp. 326–36.

the presence of raindrop impressions or of any other evidences suggesting deposition under shallow-water conditions.

Perry next calls attention to the exposures at the Ridenour Mill, on Little Fourmile Creek, about 7 miles north-northwest of Oxford, where numerous layers in the upper part of the Waynesville and lower part of the Liberty divisions of the Richmond group are ripple-marked.

Next, Perry cites the presence of mud-cracks from a locality near Moores Hill in Dearborn County, in Indiana, presumably from the Waynesville division of the Richmond group. And, finally, he alludes to the well-known ripple-marks in the upper part of the Cynthiana formation, at Ludlow, Kentucky.

Now, whatever may be the opinion concerning the value of ripple-marks as evidence of shallow-water conditions, there can be no difference of opinion as to the evidence presented by raindrop impressions and mud-cracks. However, the presence of raindrop impressions and of mud-cracks must be fully proved. This the present writer has been unable to do.

Specimens formerly interpreted by him as exhibiting raindrop impressions he now regards as ripple-marked, irregular ripples of short amplitude crossing at various angles, leaving intermediate more or less circular hollows. If anyone has clear evidence of the presence of raindrop impressions in Cincinnatian strata, this evidence should be published, accompanied by clear illustrations.

As regards the presence of mud-cracks, the present writer has seen many occurrences of structures suggesting mud-cracks, but has come to regard their origin from exposure of mud-flats to aerial conditions as extremely doubtful.

When mud exposed to the drying effects of the open air cracks, it not only tends to pull apart at the cracks, but the upper, more rapidly drying part tends to pull away from the part beneath. Frequently the cracked surface becomes sufficiently hardened to remain more or less intact when the next tide proceeds to cover it. This causes the subsequently deposited material to settle in part in the cracks, and frequently the part filling the cracks is sufficiently different to be readily distinguished from the original mud deposit.

In the case of sea deposits, the material filling mud-cracks might include coarser-grained deposits or organic material, either entire or fragmental. Now, it is the very frequency of the supposed mud-cracks with the absence of the concurrent phenomena here indicated which throws doubt on their interpretation. In such "mud-cracks" as have been observed hitherto, the material filling the cracks is essentially the same material as that forming the lateral walls of the crack, and no fossil or fragmental material has ever been found in a position suggesting that it had been dropped into the crack, or had been washed into it.

On the contrary, in many cases it has appeared possible that the cracking could have occurred subsequent to the deposition of the overlying strata, in fact long subsequent to the latter, and may not be due to the drying effects of the air along a seashore, but to shrinkage of strata deposited in much deeper waters. Mud deposits in quiet waters have been known to crack without exposure to the air, although the observed cracks have always been of too small magnitude to suggest mud-cracks. Shrinkage, however, may have occurred also long subsequent to the deposition of the overlying strata, during a period of elevation of the entire mass of marine deposits. The gradual filling of the cracks might have been accomplished by slowly circulating waters while the shrinking material still was comparatively soft. While the method of filling of these cracks may vary in different cases, the possibility of their origin from shrinkage long after the deposition of the strata in which they occur should be considered. If anyone has any evidence of the presence of mud-cracks in Cincinnatian rocks which unquestionably are due to elevation of mud flats above water-level before the deposition of the immediately overlying strata, this evidence should be published in detail.

Until the presence of raindrop impressions and of mud-cracks due to exposure of mud-flats to the open air before the deposition of the overlying strata has been proved unequivocally, it is not so certain that ripple-marks indicate shallow-water conditions. They may have been formed a considerable distance below sea-level, at least sufficiently far not to necessitate the immediate presence of a shore line.

Formerly, pebbles were regarded as unequivocal evidences of the proximity of a shore line, but even these may be formed below water-level. This is true especially of the pebbles found in the Ordovician strata of Ohio, Indiana, and Kentucky, since these usually occur only in ripple-marked layers, or in lateral extensions of these layers. The same causes which gave rise to the ripples may have given rise to the pebbles.

These causes apparently include a more or less rapid flow of water. The ripple-marked layers usually consist of more or less fragmental detrital or organic material, frequently in much greater quantity and of coarser grain than in the immediately overlying and underlying layers, as though freed from the accompanying calcareous and argillaceous muds by repeated rewashings of the materials constituting the ripple-marked layers. These muds either were washed to more distant areas or were, in part, held in suspension in the overlying waters for a short time. The ripple-marked layers frequently show evidences of cross-bedding, especially immediately beneath the crests of the ripples, thus also suggesting current action. The larger pebbles, a foot or more in diameter and only an inch or two in thickness, may easily have been formed by currents dissecting a more or less fine-grained stratum, and leaving remnants of the latter more or less imbedded in the current-washed material farther on. In limestone layers not exceeding four inches in thickness, even directly beneath the crests of the ripples, the larger pebbles scarcely could incline very much. The source of the pebbles readily could have been some formerly existent layer located less than a foot above the present level of the pebble. The finer muds of the intervening section could have been washed away, and the coarser material retained to form the major part of the ripple-marked layer, in the upper surface of which the limestone pebbles are imbedded.

Especial attention should be called to the fact that, even where the ripple-marked layers are most abundant, many of the intermediate limestone layers may show no trace of ripples. Hence, the frequent absence of ripple-marks needs explanation fully as much as their locally more or less frequent presence.

One of the causes giving rise to widespread current-action may have been violent and widespread storms. Considering the fact that the Cincinnatian strata were deposited in epicontinental seas, storms easily, at times, might have blown vast quantities of water over those parts usually covered only by shallow waters. Such storms occasionally are experienced on the Gulf coast, and along the coast of the southern Atlantic states. The ebb flow of these accumulated waters, after the storm, might easily give rise to widespread ripple-marking of the last deposited strata, even at a considerable distance from actual shore lines. Such an origin of currents would predicate wide areas of gradually shallowing seas over which the surface waters blown before the wind would tend to accumulate. Currents due to such causes might be expected more readily in the comparatively shallow waters of epicontinental seas than along the more abrupt shores of the deeper oceanic basins.

The presence of numerous well-preserved colonies of *Protarea* and of delicate growths of *Stomatopora* and other bryozoans on the upper surface of the pebbles at the Elk Run locality, east of Winchester, Ohio, is indicative of submerged conditions at least immediately after the formation of the pebbles. In a similar manner, the long crinoid columns found on the surface of the ripple-marked layers of lower Trenton limestone, at Hull, in Canada,[1] indicate that fairly deep waters were present immediately after the formation of the ripple-marks, and may have been present even during their formation.

Ripple-marks comparable in dimension with those characteristic of the Ordovician limestones of Ohio, Indiana, and Kentucky are not unknown along our present shores. They occur where waters accumulating in extensive salt marshes or in estuaries during high tide find a ready outflow to the sea during ebb conditions. In these cases the steeper slopes of the ripple-marks are directed away from the shallower waters.

It is remarkable, however, in the case of the ripple-marks on the Ordovician limestones of the areas here under discussion, how

[1] Kindle, *Jour. Geol.*, XXII (1914), 712.

slightly the slopes on the two sides of the crests of the latter differ in most cases. Frequently it is difficult to determine a difference in slope at all, and rarely is this difference strongly defined, as in the case of the strong ripples found after ebb tide along our present coasts.

Eventually it may be possible to accumulate sufficient evidence to determine with considerable certainty the conditions under which many of the strata of ancient days were deposited. To many the evidence appears to be already at hand. To others a revision of the evidence may appear necessary. To the writer it appears desirable that those who have indubitable evidence of land conditions during the deposition of Ordovician strata in the states of the Ohio Valley should publish the same. This is true especially in case of raindrop impressions and of mud-cracks, which are favorite evidences locally of shore and land conditions during Ordovician times.

Reviews

Upper White River District, Yukon. By D. D. Cairnes. Geol. Survey Canada, Memoir 50, 1915. Pp. 191, figs. 2, pls. 17, maps 3.

This report covers an area of about 800 square miles lying along the Alaska-Yukon International Boundary from latitude 61° 40′ to 62° 30′. It is considered to be a promising area for mineral deposits of economic value.

The oldest rocks exposed are mica schists referred to the Yukon group of pre-Cambrian age. Upon these rest 1,500 feet of Carboniferous limestones and clastics followed by 1,000 feet of Mesozoic shales and sandstones. At a few points Tertiary beds were observed. These beds are in part flat-lying, and in part have been highly dynamically metamorphosed.

The writer believes that the Nutzotin Mountains are due to differential erosion rather than to faulting. They remained as a region of considerable relief at the time of the peneplanation of the Yukon plateau region and were further uplifted between the late Miocene and the early Pleistocene. A different explanation from that suggested by geologists of the United States Geological Survey is advanced to account for drainage changes along White River.

W. B. W.

Wyoming and McDowell Counties. By R. V. Hennen. West Virginia Geol. Survey, 1915. Pp. 783, pls. 31, figs. 28, maps 2.

McDowell County, situated on the southern border of the state, has led all the counties in the state in coal production since 1905. Approximately 15,000,000 tons were produced in 1915, and at this rate its available coal will last about two hundred and fifty years. Wyoming County coal fields have not been developed until recently, but its coal reserves equal those of McDowell County.

The Pottsville series has a remarkable development here. It increases from a thickness of 250 feet at the northern edge of the state to a maximum of 3,850 feet in these counties. It has been differentiated into three groups and two score formations.

A new feature in this report is a series of 25 maps of these counties showing the minable coal areas of as many different coal horizons. Under separate cover are topographic and geologic and structure contour maps.

W. B. W.

Oil and Gas Fields of Ontario and Quebec. By WYATT MALCOLM. Geol. Survey Canada, Memoir 81, 1915. Pp. 248.

This memoir has been prepared chiefly for those interested in the commercial development of oil and gas. It treats of the lithology, stratigraphic relations, and areal distribution of the geologic formations from the Potsdam to the Chemung. The predominant structural feature is a gentle dipping of the strata to the southwest away from the pre-Cambrian axis. The northeastern extension of the Cincinnati anticline reaches into Ontario.

The productive horizons are not limited to one formation. Gas is found in the Medina, oil and gas in the Guelph and Salina, and oil in the Onondaga. The production of gas has increased steadily, but the oil output reached a maximum in 1907, and since then has fallen greatly.

Analyses of gas from different fields show a surprising uniformity of composition. The writer of the report believes this to be incompatible with a local and separate origin of the gas for each field.

W. B. W.

Arisaig-Antigonish District, Nova Scotia. By M. Y. WILLIAMS. Geol. Survey Canada, Memoir 60, 1914. Pp. 173, maps 2.

The chief interest in this memoir lies in its contribution to stratigraphy. Careful attention had been given already to the region, for in it lies the key to the stratigraphy of a considerable area. The purpose of this investigation was to work out in still greater detail the sedimentary record and the ages and relations of the igneous rocks.

Of the Paleozoic systems, the Cambrian and Permian are missing. Where possible, correlations are made with the type sections of Europe. Separate chapters are reserved for structural and historical geology. Igneous geology is given the same careful attention as the sediments. The igneous rocks are limited largely to acid and basic intrusives in the Ordovician, and to intrusive diabase sheets in the Mississippian.

W. B. W.